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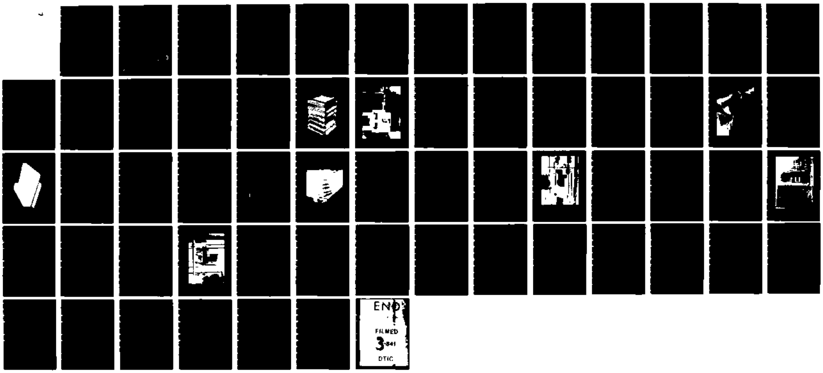

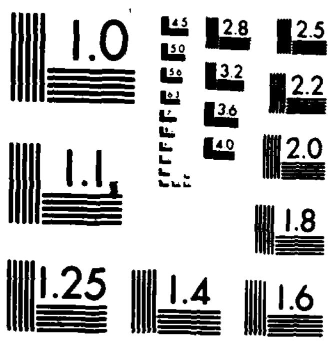


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AMMRC TR 84-1

# CREW SURVIVABLE HELICOPTER UNDERCARRIAGE

January 1984

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LTV Vought Corporation
P.O. Box 225907
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FINAL REPORT

Contract No. DAAG46-82-C-0047





Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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ABSTRACT

The program goal was to demonstrate the energy absorbing capability of the Vought "rotated" sine wave concept for helicopter fuselage undercarriage structure. Specific program objectives were to develop design and manufacturing procedures for energy absorbing aluminum structure, fabricate and test specimens to confirm the methods and relate the slow and high rate test results to undercarriage structure designed to meet MIL-STD-1290 criteria. The specimens were fabricated in a standard sheet metal shop, without special attention. There are several cost and weight advantages asscociated with the sine wave concept. The cost savings relative to conventional metal design are attributable to the reduction in number of parts and fasteners which saves material dollars and assembly hours. The high-rate and slow-rate testing of the test elements verified the performance of the energy absorbing structure developed in this program. The selected skin gage to meet the 200 lbs/in. running load requirement is 0.063 inch. The substructure will carry normal flight loads and provide the energy absorbing capability when necessary.

## FOREWORD

This final technical report covers the work performed under contract DAAG46-82-C-0047 from July 1982 through October 1983. This contract with LTV Vought Corporation was conducted under the technical direction of Mr. A. A. Anctil of the Army Materials and Mechanics Research Center in Watertown, Mass.

This program was accomplished by the Structures Research and Development Group and the Advanced Manufacturing Techrology Group of Vought Corporation. Mr. J. L. Maris was responsible for the specimen design and analysis. Mr. P. S. Waldrop was responsible for specimen fabrication. The high strain rate testing was conducted at the Army Structures Laboratory located in the NASA Langley Research Center under the direction of Dr. G. L. Roderick and Mr. G. L. Farley. They provided the test equipment and data acquisition system. Mr. B. T. Gannon was responsible for final test data reduction and reporting. Mr. M. Poullos was the program manager.

The program was undertaken to investigate and verify the energy absorbing capability and manufacturing potential of the rotated sine wave concept.

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# 1.0 INTRODUCTION AND SUMMARY

## 1.1 Purpose and Objectives

The purpose of this program was to validate the energy absorbing capability, structural integrity and weight advantage of advanced technology aluminum structures. The program goal was to demonstrate the energy absorbing capability of the Vought "rotated" sine wave concept for helicopter fuselage undercarriage structure. Specific program objectives were to develop design and manufacturing procedures for energy absorbing aluminum structure, fabricate and test specimens to confirm the methods and relate the slow and high-rate test results to undercarriage structure designed to meet MIL-STD-1290 criteria.

## 1.2 Program Description

Vought Corporation conducted a program for the Army Materials and Mechanics Research Center (AMMRC) to design, fabricate and test crash survivable specimens representative of helicopter undercarriage structure using the Vought metallic "rotated" sine wave concept. The effort was divided into seven tasks which were performed over a span of sixteen months. The schedule is presented in Figure 1. The following paragraphs briefly describe each task.

### 1.2.1 Task 1 - Undercarriage Design and Manufacturing Development

This task was a joint, iterative effort between Structures Engineering and Manufacturing Engineering personnel to define an energy absorbing

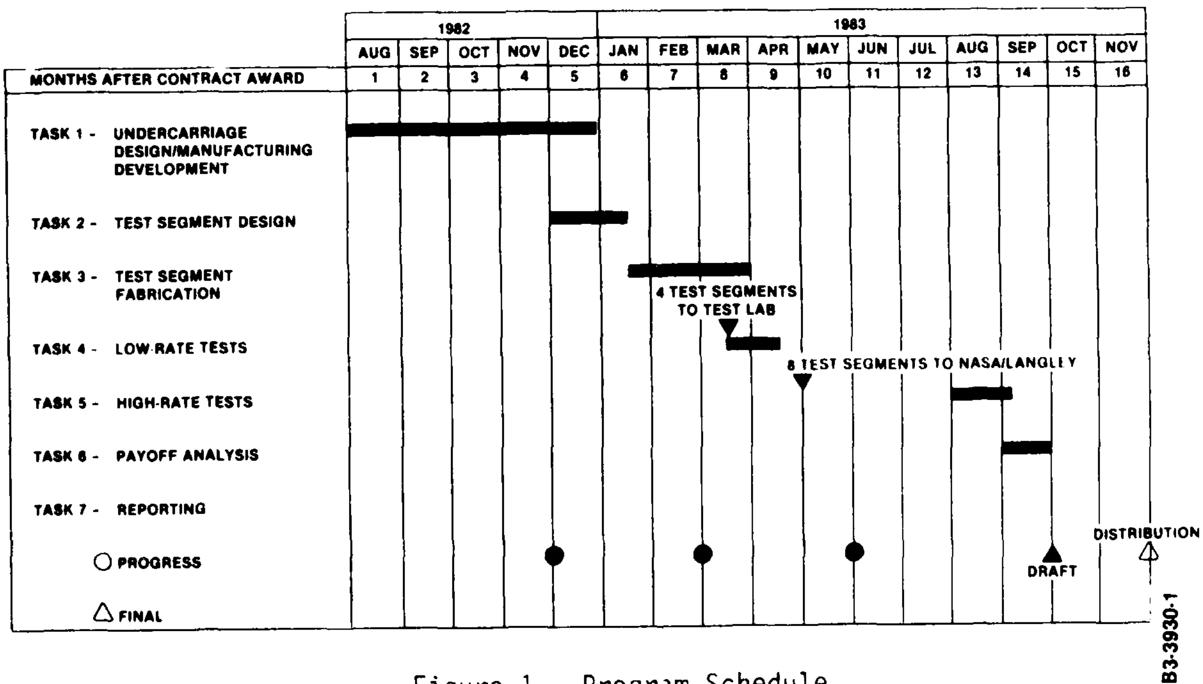


Figure 1. Program Schedule

undercarriage design approach. Definition was based on prior structural test data, analysis, and the results of tool and sheet metal forming trials conducted prior to and during this task. Emphasis was placed on the development of a highly fabricable joint configuration compatible with the required crush characteristics of the undercarriage structure.

The results were incorporated in a structural layout drawing which depicts longeron and bulkhead spacing, thicknesses, and joint configuration. Design criteria (geometry, loads, weights, etc.) developed from Vought's involvement in the Sikorsky ACAP program were utilized in defining this baseline design layout.

### 1.2.2 Task 2 - Test Segment Design

In this task a representative segment of the undercarriage structure was designed for physical test and evaluation. The segment design represented the full scale approach established in Task 1 as closely as practical. The joint configuration was representative of a production airframe.

### 1.2.3 Task 3 - Test Segment Fabrication

Thirteen test segments, six from 0.063 gage and seven from 0.040 gage material, were fabricated from 6061 aluminum sheet for crush testing. The task included necessary tool fabrication or modification of tooling from Task 1, fabrication of detail parts and assembly of the test components. The forming die consisted of an innovative, cast epoxy tool. Detail fabrication included rubber press forming of the longeron/bulkhead segments with integral flanges and corrugated webs, followed by trimming and heat treating. Assembly was accomplished with mechanical fasteners.

### 1.2.4 Task 4 - Slow-Rate Tests

Slow-rate testing of the segments was conducted at Vought to determine failure modes and energy absorption efficiency. The segments were crushed from their original 14 inch height to approximately 4 inches. Load versus deflection curves were plotted over the full stroke for each specimen. Five segments (two of one gage and three of another) were tested in this manner. The results from these tests were compared to analytical predictions and other literature data to determine the efficiency of the selected design.

### 1.2.5 Task 5 - High-Rate Tests

Once feasibility was established with the slow-rate testing, eight specimens (four of each gauge) were sent to the Army Structures Lab at NASA Langley Research Center for high-rate testing. Vought engineers witnessed these tests and were available for technical evaluation and assessment.

### 1.2.6 Task 6 - Pay-off Analysis

Upon completion of the testing, results were analyzed and compared to analytical predictions and data from other energy absorbing structure programs. The undercarriage layout was sized to reflect the high-rate test results. Projections for cost and weight savings were estimated at 25% weight savings and 15% cost savings compared to current sheet metal structure.

### 1.2.7 Task 7 - Reporting

Three quarterly reports and this final technical report were prepared summarizing the results of this effort.

### 1.3 Summary

The "rotated" sine wave concept utilized in this program grew out of Vought in-house manufacturing technology programs and a previous Air Force funded contract (1979) related to advanced technology wing structure. This AMMRC program designed, fabricated and tested "box" specimens to verify the energy absorbing capability of this current concept.

The Vought-developed technique utilizes plastic produc n tooling to produce net formed, integrally flanged sine wave undercarr ge components, i.e, longeron and bulkheads. This type of fabrication prc es a lightweight, highly efficient load bearing structure that is superior ( qual to composite honeycomb sandwich or conventional sheet/stringer aluminu struction in compressive energy absorption capacity.

Table 1 summarizes all the test data generated in this program. Seven specimens representative of the aluminum sine wave concept were slow-rate tested at Vought, two were fabricated and tested under IRAD and five were program specimens. Test results were used to refine the high-rate test specimens and were compared to other literature data on a specific load per length and energy per inch of perimeter of stroke basis. The program test results compare favorably to the literature survey and the sine wave concept is the most economical to fabricate and incorporate into the fuselage structure.

High-rate testing of eight specimens was conducted at NASA Langley. The results were 16 to 33 percent better than expected; however, the test equipment did not apply the energy as anticipated. The test equipment was set up and calibrated with 226 pounds of weight on the drop table. At this weight, the drop table is 90 percent heavier than the 119 pounds required for the 0.040 gage specimens; consequently, more energy than anticipated was applied to the specimens.

The drop table was 26 percent lighter than the 308 pounds required for the 0.063 gage specimens; thus the 0.063 gage specimens displaced only 6.2 inches instead of the design value of 11.0 inches and the peak "g" loading was 35 g's. The overall program results validate the design procedure and the data provides a solid basis for proceeding to Phase II.

TABLE 1. TEST DATA SUMMARY

| Specimen No | Skin Gage In. | Fastener | | Load Rate | Load Lbs. | Perimeter In. | Running Load Lbs./In. |
|---|---|---|---|---|---|---|---|
| | | Type | Location | | | | |
| 1. | .040 | Blind | Tangency | Slow | 3255 | 42.0 | 77 |
| 2. | ,063 | | " | | 9155 | 44.0 | 208 |
| 3. | .040 | | Peak & Valley | | 2268 | 39.8 | 57 |
| 4. | .063 | | " | | 7482 | | 188 |
| 5. | .040 | | Tangency | | 2985 | | 75 |
| 6. | .063 | Blind | | | 7005 | | 176 |
| 7. | .040 | Hilok | | Slow | 3502 | | 88 |
| 8. | | | | High | 5373 | | 135 |
| 9. | | | | | | | |
| 10. | | | | | | | |
| 11. | .040 | Hilok | | | 5373 | | 135 |
| 12. | .063 | Blind | | | 9273 | | 233 |
| 13. | | Hilok | | | | | |
| 14. | | " | | | | | |
| 15. | .063 | " | Tangency | High | 9273 | 39.8 | 233 |

# 2.0 DESIGN DEVELOPMENT

## 2.1 Design Criteria

The Sikorsky ACAP helicopter was selected as the baseline vehicle for this program since Vought had just completed an energy absorbing substructure design for it. Figure 2 illustrates the area designed to be energy absorbing. This conforms to the MIL-STD-1290 requirement to protect the aircraft occupants from injury during a crash impact up to and including the 95th percentile potentially survivable accident, while minimizing aircraft structural damage.

The design condition is a 42 foot/second (fps) vertical drop with the landing gear slowing the fuselage to 31 fps at impact. Figure 3 shows the proposed vertical speed and angular attitude envelope requirements the helicopter must meet. The ACAP design for crushable under-the-floor structure is shown in Figure 4. The energy absorbing design to meet the 31 fps requirement is 200 pounds per linear inch of bulkhead/longeron substructure with an average crushable height of 4 inches. A portion of the structure below the floor (approximately one-half) was designed to remain intact during the crush to strengthen the floor. The rotated sine wave concept of this program utilizes all structure below the floor as crushable since it remains structually effective after it is crushed, i.e., adequately supporting the floor as a beam. The following load per running length requirements were selected for the evaluation with test specimens which are representative of bulkhead/longeron configurations:

- 200 lb/in - to match ACAP design
- 100 lb/in - assumes twice the crushable height

A structural layout of the crew survivable substructure was prepared to establish the bulkhead and longeron structural arrangement. This layout determined the geometry of the test elements.

## 2.2 Preliminary Test and Evaluation

A preliminary test specimen was fabricated under IRAD from 0.063 inch thick 6061 aluminum and slow-rate tested. The approximate dimensions were 6 inches by 6 inches with a 14 inch height, 11 inch stroke, and welded at the corners. The specimen carried an average load of 4517 pounds over an 8 inch stroke. This converts to a running load of:

$$\frac{4517 \text{ lb}}{(4)\ 6 \text{ in}} = 188.2 \frac{\text{lb}}{\text{in}}$$

This data, including load, geometry, and material thickness, was used to determine panel thicknesses for the program specimens. The specimen dimensions were set at 12 inches wide by 12 inches long to save on tooling costs and a 14 inch height, 11 inch stroke, to represent geometry that could be utilized in helicopter substructure.

The following calculations were performed to determine panel thickness requirements for the thin and thick gage specimens utilizing the preliminary test results. They also account for the material overlap of the fastened joint versus welded construction.

Figure 2. Energy Absorbing Substructure Area

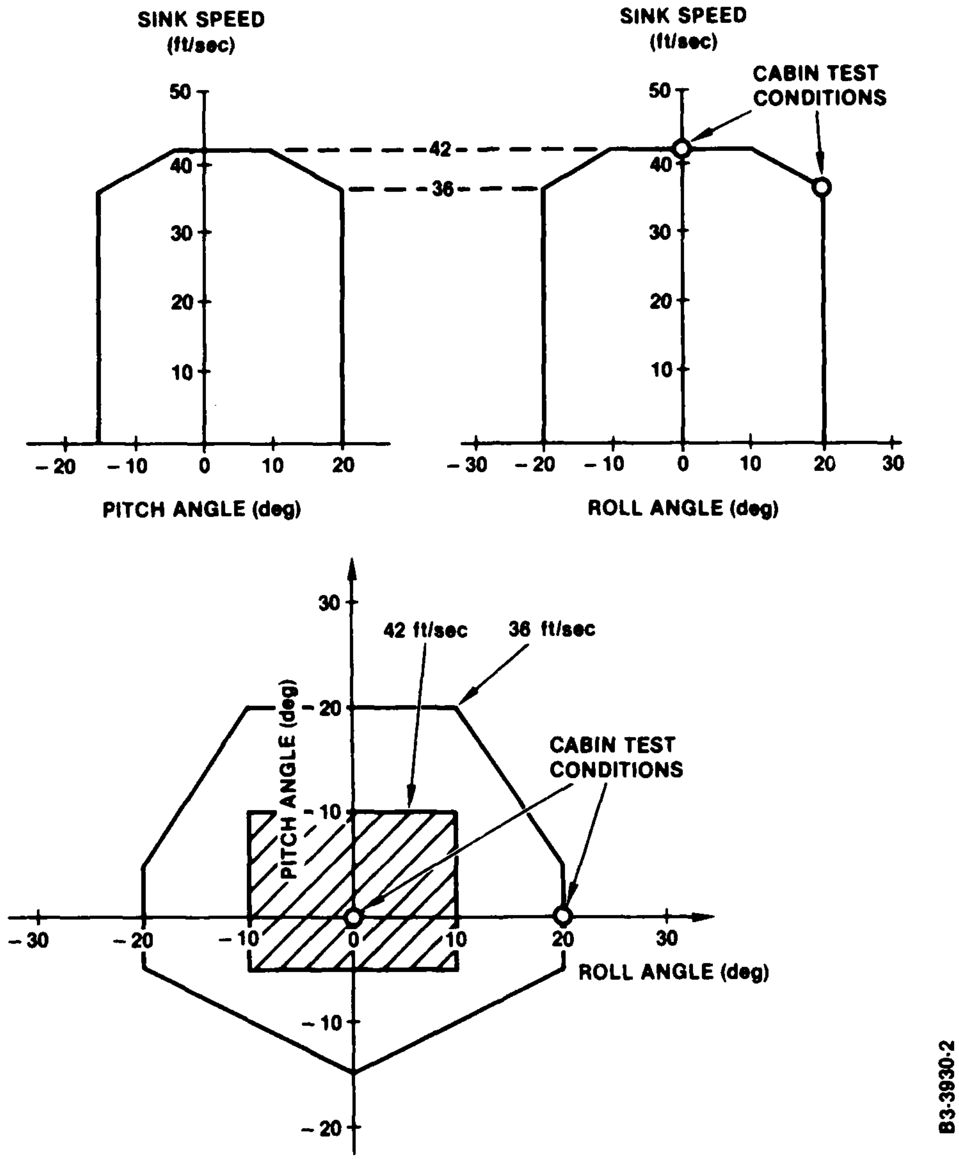


Figure 3. Proposed MIL-STD-1290 Revision Roll and Pitch Envelope for Vertical Crash Impact Conditions

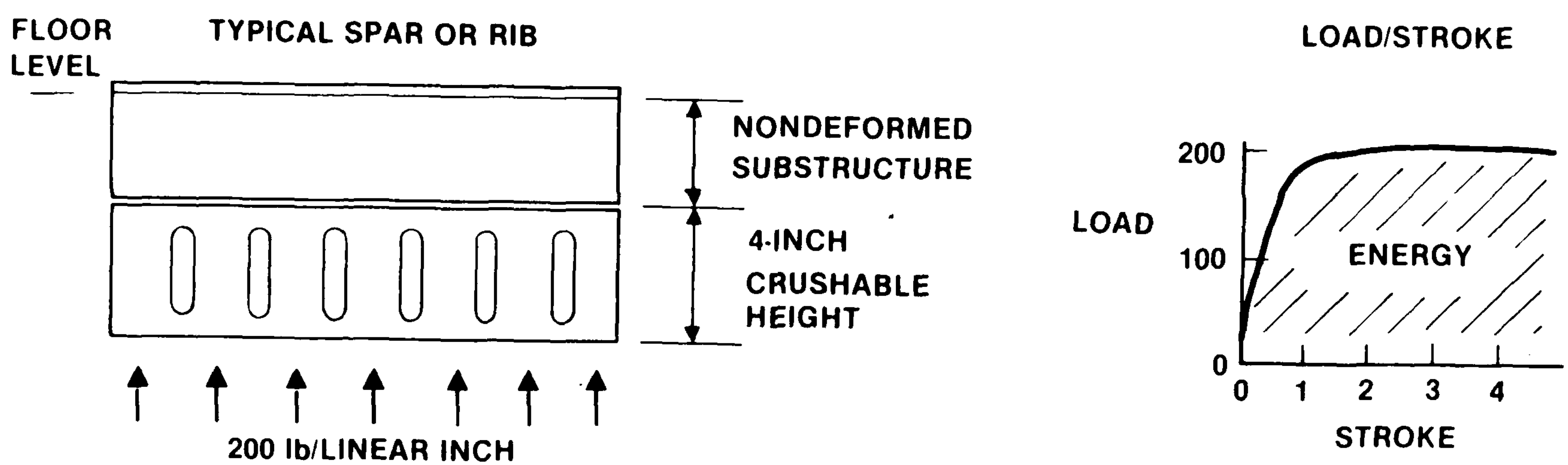


Figure 4. ACAP Design Concept

## 2.3 Analysis

Total running length including overlap is

(4) 12 inches + (4) 1.75 inches = 55 inches

The running length ratio (to simplify thickness calculations) is

$$\frac{55 \text{ in}}{48 \text{ in}} = 1.146$$

For the 200 lb/in specimens

$$\frac{200 \frac{\text{lb}}{\text{in}}}{1.146} = 174.55 \frac{\text{lb}}{\text{in}}$$

From preliminary test data, the material thickness is

$$(188.21) \frac{t_1^2}{0.063^2} = 174.55$$

$$t_1 = 0.061 \text{ inch}$$

The selected thickness was 0.063 inches because it is a standard gage.
For the 100 lb/in specimens:

$$\frac{100 \frac{\text{lb}}{\text{in}}}{1.146} = 87.26 \frac{\text{lb}}{\text{in}}$$

From test data, the calculated material thickness is

$$(188.21) \frac{t_2^2}{0.063^2} = 87.26 \frac{\text{lbs}}{\text{in}}$$

$$t_2 = 0.043 \text{ inch}$$

The selected thickness was 0.040 inches because it is a standard gage.

These two selected thicknesses provide design data that can be used to select an appropriate thickness for a specific requirement.

Two additional preliminary test specimens, as shown in Figure 5, were fabricated. One was made from 0.063 inch thick 6061 aluminum with blind rivets. The other was made from 0.040 inch thick 6061 aluminum with the same fasteners. Both were slow rated tested as shown in Figure 6.

Figure 7 presents the load/deflection plot of the 0.063 inch gage specimen. The average load through 9.0 inches of stroke was 9155 pounds. The specimen running length was 44.0 inches; consequently, the running load per inch is 9155 lbs/44 in. = 208 lb/in, which corresponds to the design goal of 200 lb/in. In addition, the energy efficiency was excellent, approaching the theoretical 100% of a rectangular shape under the curve. The effectiveness of

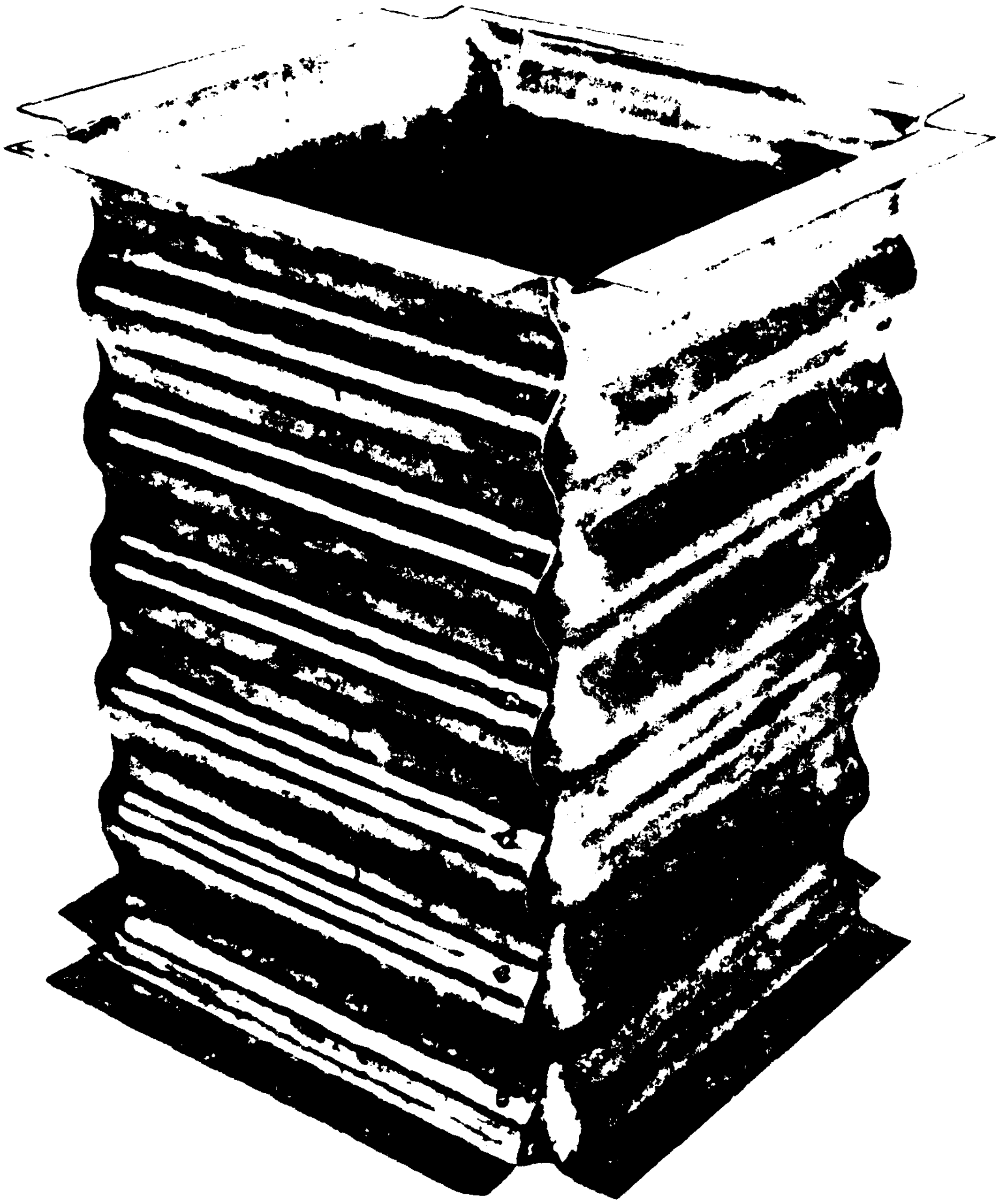

Figure 5. Prototype Test Segment No. 1, 0.063 Inch Gage, 12" x 12" x 14"

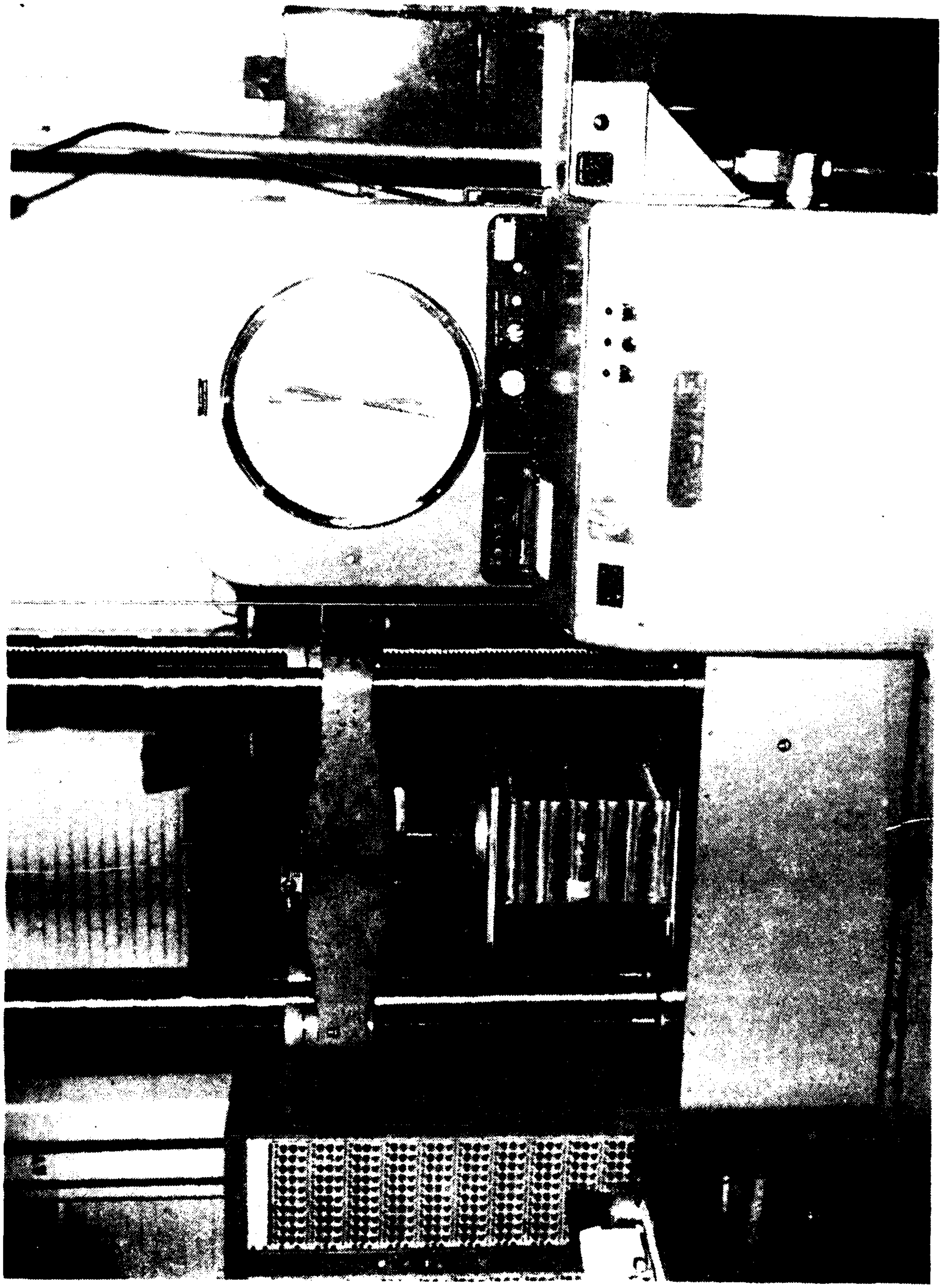

Figure 6. Test Setup and Specimen

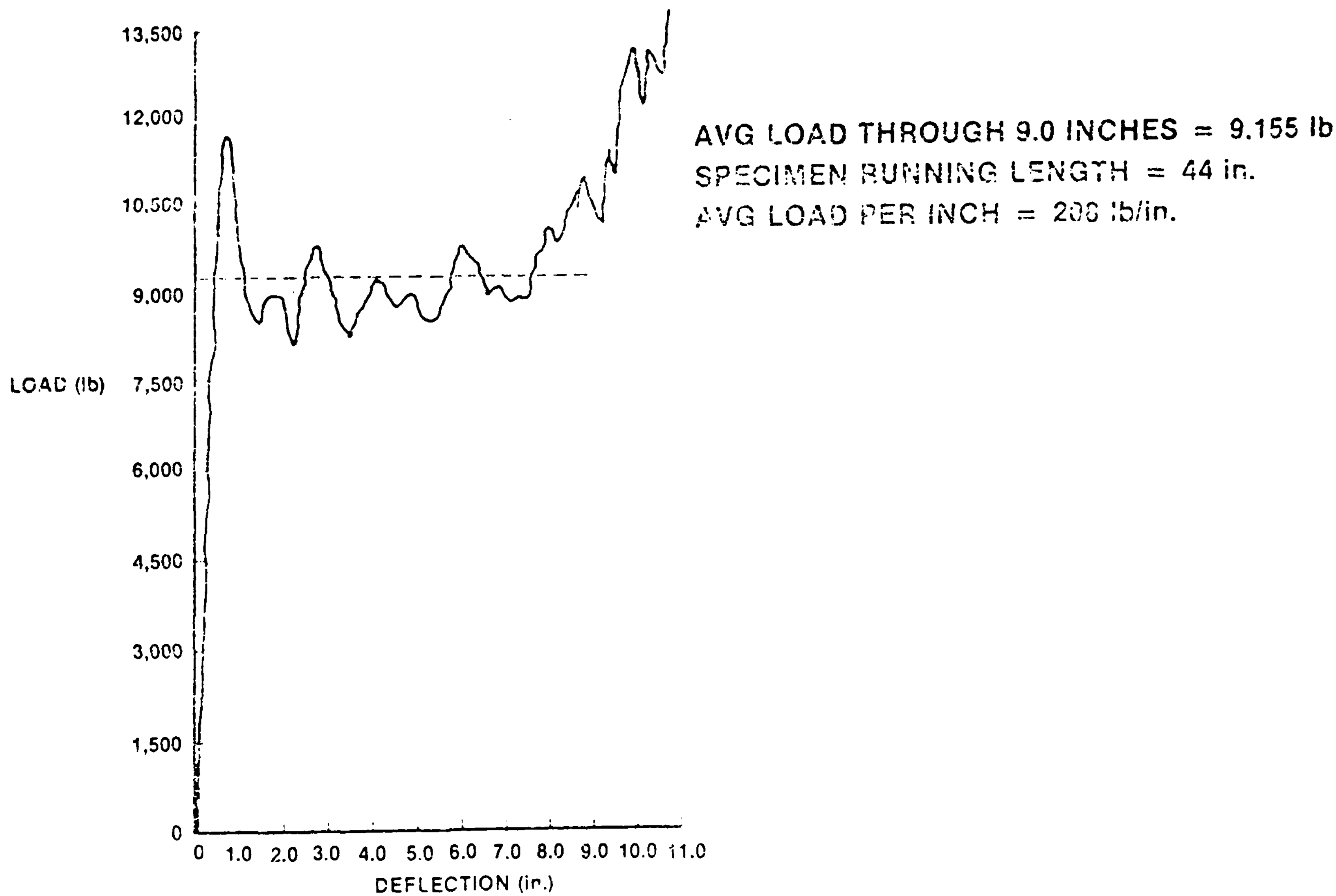


Figure 7. Load vs. Deflection, Slow-Rate Test, 0.063 Inch Gage Specimen

the joint was established because, even after full crush, no tearing of the sheet or failure of the fasteners occurred. This demonstrated that the crushed structure will still be an effective structural element to support the cabin floor. The initial spike was due to the additional load required to initiate the crush. The spike's small area relative to the rest of the curve indicates a minor change to the structure will remove this peak.

Figure 8 is the load/deflection plot of the 0.040 inch gage specimen. The average load was 3255 pounds which results in a running load of 3255 lbs/44 in = 77.5 lb/in. This is below the design load of 100 lb/in but it correlates to the lower thickness of the actual specimen used. The overall efficiency was not quite as high as the 0.063 inch specimen, but it was acceptable. There was some fastener pull through and sheet bearing failures. The initial spike was also present in this specimen.

## 2.4 Final Segment Design

The following changes were incorporated into the final test segments. The overall dimensions of the segments were reduced to 11 inches wide by 11 inches long to fit the test machine at the Army Structures Lab at NASA Langley. A decision was made to vary the location and type of fasteners on the slow-rate test specimens. The results and conclusions are discussed in Section 4.1 of this report and were used in fabricating the high-rate test specimens.

Vent holes were added to the high-rate test specimens. A total of 20 holes, 0.56 inches diameter each, with 5 on each side of the specimen, were drilled in each specimen at the sine wave peaks. (Sixteen holes of 0.625 inch diameter were located in the valleys of the slow-rate test specimens). The holes provided vents for the air as the specimens were compressed during the high-rate testing, therefore avoiding a high spike load.

The following analysis was performed to determine the effect on the performance of the high rate specimens due to air entrapment.

Drop rate = 32 ft/sec = 384 in/sec

Cross sectional area of box = 98 $in^2$

Air Volume Rate = (98 $in^2$) 384 in/sec = 37,632 $in^3$/sec

Dynamic pressure $q = 25 \left(\frac{V}{100}\right)^2$ $lbs/ft^2$ (Units of V = mph)

Velocity was determined by dividing the Air Volume Rate ($in^3$/sec) by the selected Vent Area ($in^2$) and converting to mph.

For Vent Area = 5.0 $in^2$

$$\text{Velocity} = \frac{37632\ in^3/sec}{5\ in^2} = 7526\ in/sec = 428\ mph$$

$$\text{Dynamic Pressure } q = 25 \left(\frac{428^2}{100}\right) = 457\ lbs/ft^2 = 3.2\ psi$$

$$\text{Instantaneous Spike Load} = 3.2 \frac{lb}{in^2} \times 98\ in^2 = 311\ lbs$$

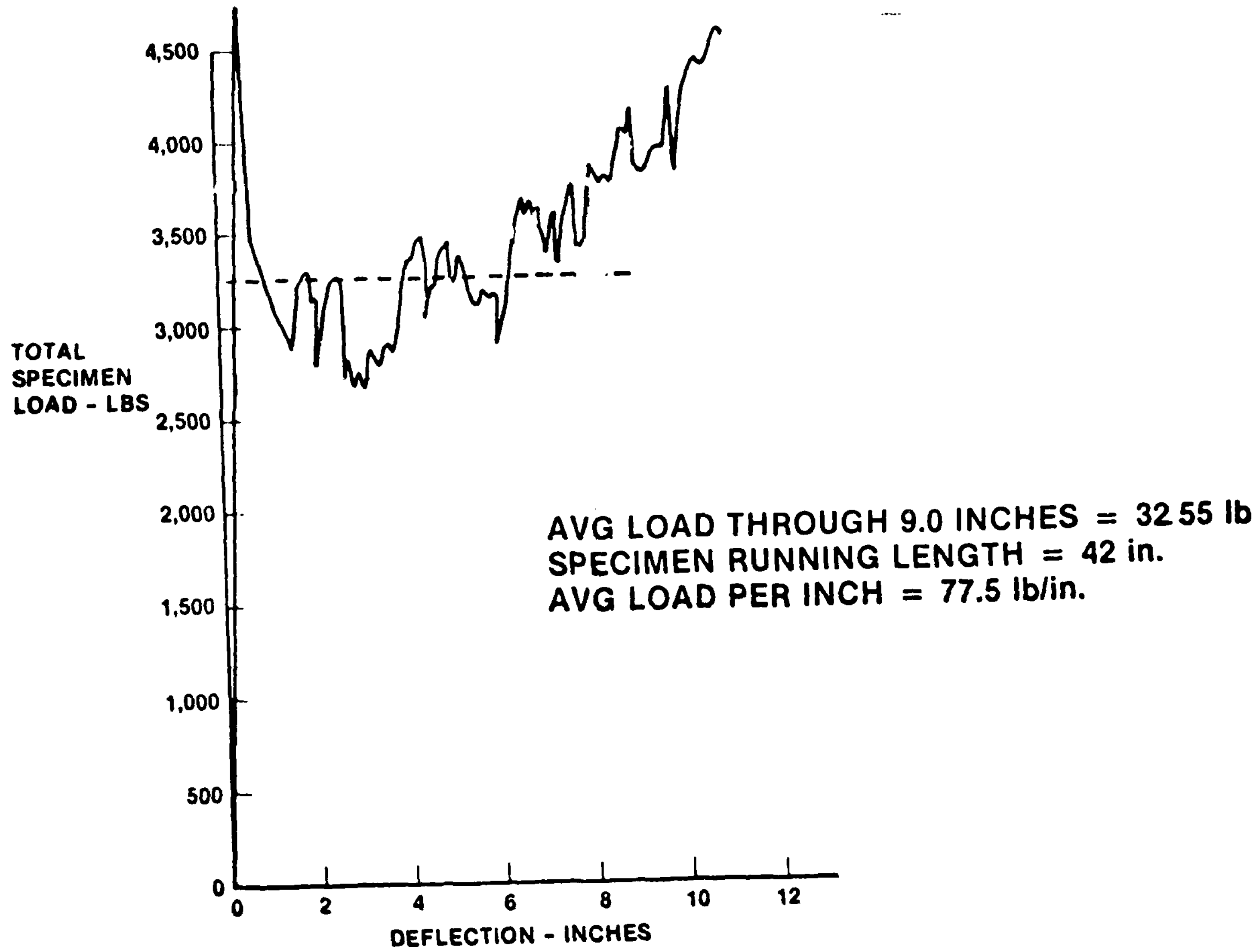


Figure 8. Load vs. Deflection, Slow-Rate Test, 0.040 Inch Gage Specimen

For the 0.040 inch thick specimens, this spike load represents the following percentage of total load:

$$\frac{311 \text{ lb}}{39.6 \text{ in X } 100 \frac{\text{lb}}{\text{in}}} \text{ X } 100 = 8.0\%$$

For the 0.063 inch thick specimens this spike load represents the following percentage of total:

$$\frac{311 \text{ lb}}{39.6 \text{ in X } 200 \frac{\text{lb}}{\text{in}}} \text{ X } 100 = 4.0\%$$

The holes were placed in the sine wave peaks rather than the valleys to minimize the tendency of the sine waves to fold the wrong way locally at the vent holes, as observed on the slow-rate test.

## 2.5 High-Rate Test Calculations

The required weight of the drop table used in the high-rate tests was found by equating the kinetic energy of the drop table to the work performed during crushing (crush load times crush distance).

Kinetic Energy = Crush Load x Crush Distance

$$\frac{mV^2}{2} = mg\ G\ s$$

where

m = mass of drop table
V = velocity = 32 fps
g = acceleration of gravity = 32.2 ft/s$^2$
G = load factor
s = crush distance = 11 inches with .8 efficiency

The above equation can be rearranged to yield the load factor, G.

$$G = \frac{V^2}{2gs} = \frac{(32)^2\ 12}{2(32.2)(11 \text{ x } .8)} = 21 \text{ g's}$$

Thus, the force at impact, F, is

$$F = mgG$$

or

$$mg = \frac{F}{G}$$

For the 100 lb/in specimen, the table weight was

$$mg = \frac{(100 \frac{\text{lb}}{\text{in}} \text{ x } 39.8 \text{ in}) - 1480}{21} = 119 \text{ lbs.}$$

For the 200 lb/in specimen, the table weight was

$$mg = \frac{(200 \frac{\text{lb}}{\text{in}} \text{ x } 39.8 \text{ in}) - 1480}{21} = 308 \text{ lbs.}$$

## 3.0 MANUFACTURING ENGINEERING

The manufacturing guidelines for this program were based on the utilization of low cost tooling concepts and conventional rubber press forming equipment and processes developed at Vought. The chosen process used 6061 aluminum in the annealed condition, a hydroforming process, and cast epoxy tooling.

Critical processing parameters, including material condition, grain direction, blank configuration and forming sequence were evaluated. All forming operations were conducted at room temperature. Circle-grid etch technology was applied to the blanks in order to visualize and quantify the patterns of strain created during forming.

A prototype tool was used to refine the processing parameters. Early trials indicated a need to control the flow of material without trapping it on the tool faces. Excessive movement of the material resulted in wrinkling, and entrapment of the material resulted in tears due to stretching beyond the material's formability limits. Blanks with a scalloped edge were tried as a means of controlling the degree of holding pressure exerted by the press bladder. Further testing with simple rectangular blanks, however, showed that scalloping the edges would be unnecessary.

It was determined that a very low pressure, approximately 500 psi, would form the blank to about 90 percent of its final shape and permit acceptable flow of the blank over the die faces. The blank width was found to be a critical element. A blank width was established which would provide minimum surface for entrapment while leaving the necessary material for trimming after the second press operation.

The second forming step was performed at 6,000 psi so that the material would be completely formed into the corner radii of the die, finishing the "rotated sine wave". This step was preceded by a solution heat treatment of the 6061 aluminum to the "W" condition. The parts were refrigerated prior to forming. The second press operation removed any deformation from the heat treatment. Finished parts were aged to T-6.

The prototype epoxy tooling was modified to investigate the feasibility of incorporating integral attachment flanges in the primary forming stage. During the initial forming evaluations, the flanges were formed in a secondary operation. Using the modified epoxy forming tool, several sine wave sections with integral flanges were successfully formed. A complete preliminary crush test speciman shown in Figure 5 was assembled with blind rivet MS-20600-MP5-W2 fasteners for preliminary sizing tests.

For the purposes of producing the contract specimen detail parts, it was decided to form the end attachment flanges during the second step. There was less need for precision trimming of the blank, and less chance of a tear, in the second step. At the completion of the manufacturing investigation, tooling was built for the contract specimens.

An optically-guided router was used to create precision sine wave templates required to form the master for the cast epoxy tools. The master was formed of plaster, hand-swept with the templates shown in Figure 9. The completed plaster element was then boxed in for casting. Plaster fillets were


Figure 9. Plaster Master Tool

added to form outside corner radii on the tool to be cast. A reinforcement plate of aluminum was suspended in the casting box, and the epoxy tooling material was then poured. The completed tool, shown in Figure 10, was then removed and cured.

Two tools were produced in the above manner, which Vought has previously demonstrated to be a very effective, low cost method. The first step, shown in Figure 11, is designed to form the specimen side panels from a flat sheet to the approximate final contour. Following trim and solution heat treatment to restore ductility (Step 2), the panels are placed on the second tool (Step 3) and formed at approximately 7,000 psi. This third step bends the attachment flanges to 90$^{0}$, finishes radii detail in the rotated sine wave, and removes any heat treatment distortion.

From the finished detail parts, specimens were constructed around an assembly jig (Step 5). Plated monel blind rivets were installed, but later replaced with HiLok threaded fasteners in order to solve the problem of rivet pull through, experienced in slow-rate testing. From spare detail parts, one additional 0.040 gage specimen was fabricated in order to slow-rate test the performance of the new fastener.

The rework to replace the blind rivets with HiLoks was accomplished using the following procedures. A hole gage was used to check hole diameters after the existing fasteners were removed. If the hole diameter was smaller than 0.176 inch, the same size HiLok was installed in the hole. Otherwise, the hole was reamed out for the next size fastener. All the existing fasteners were replaced, and the 0.56 inch diameter vent holes were drilled as shown in Vought Drawing CS-001, Figure 12.

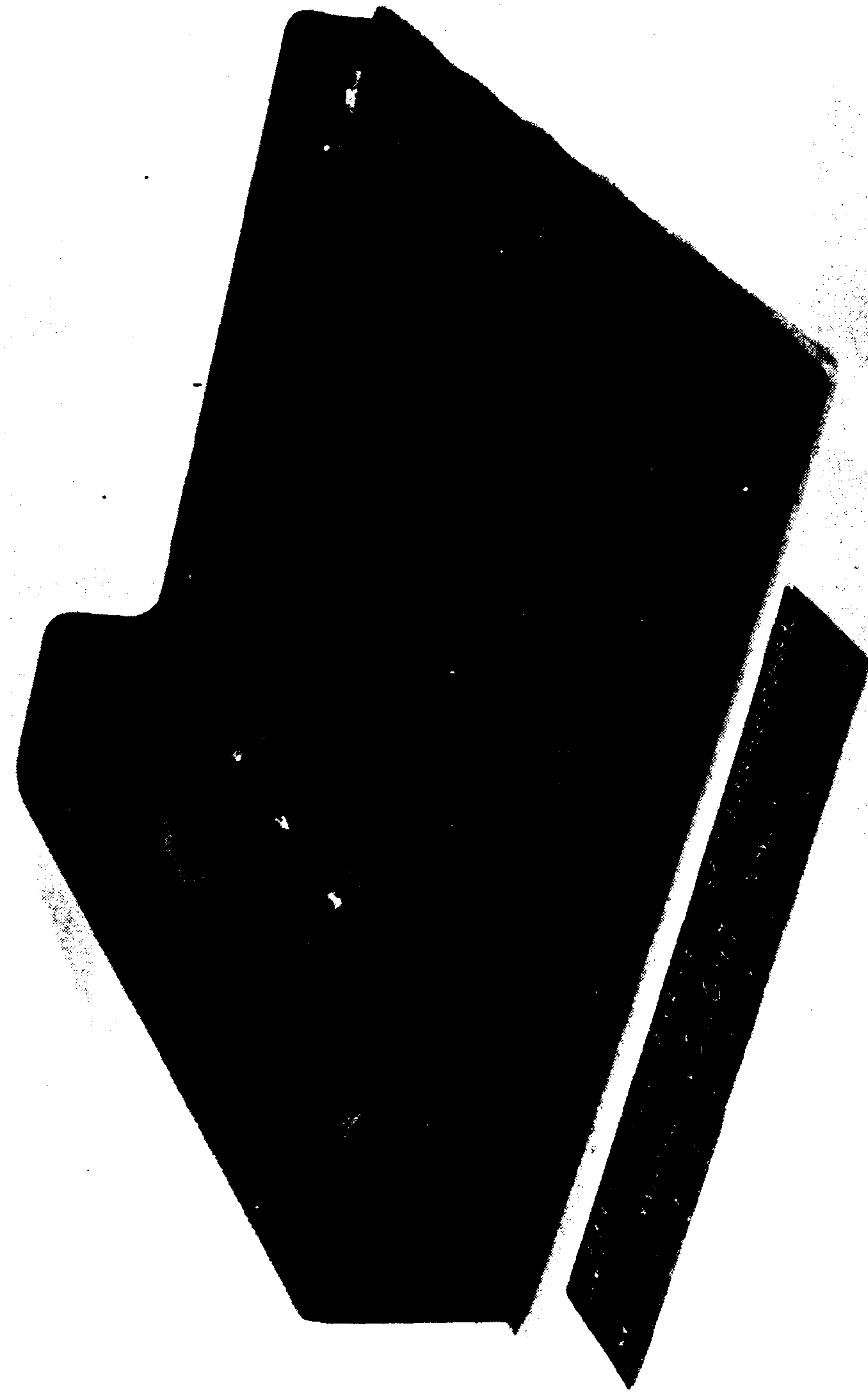

Figure 10. Epoxy Tool

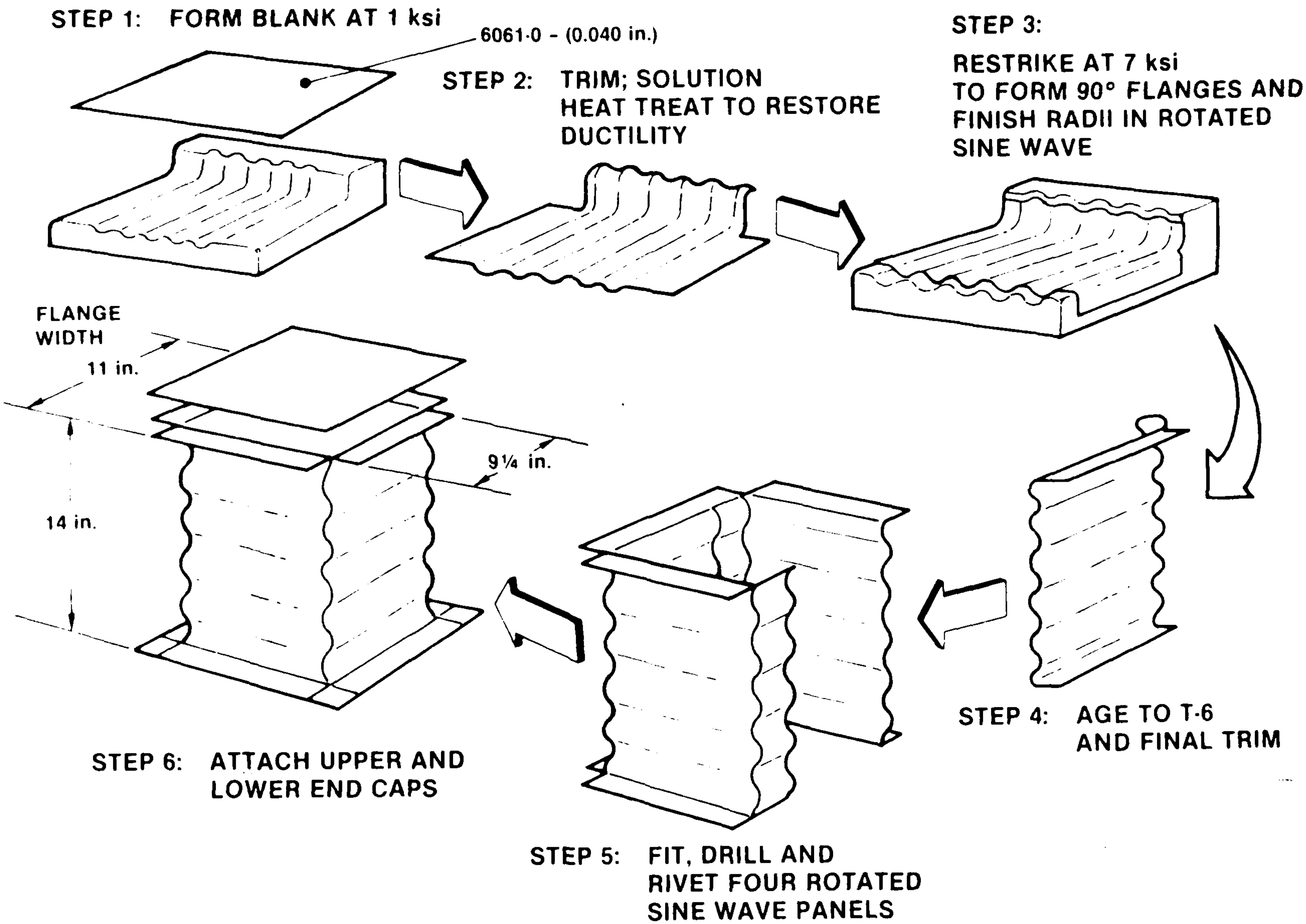


Figure 11. Crush Test Specimen Fabrication Flow Diagram

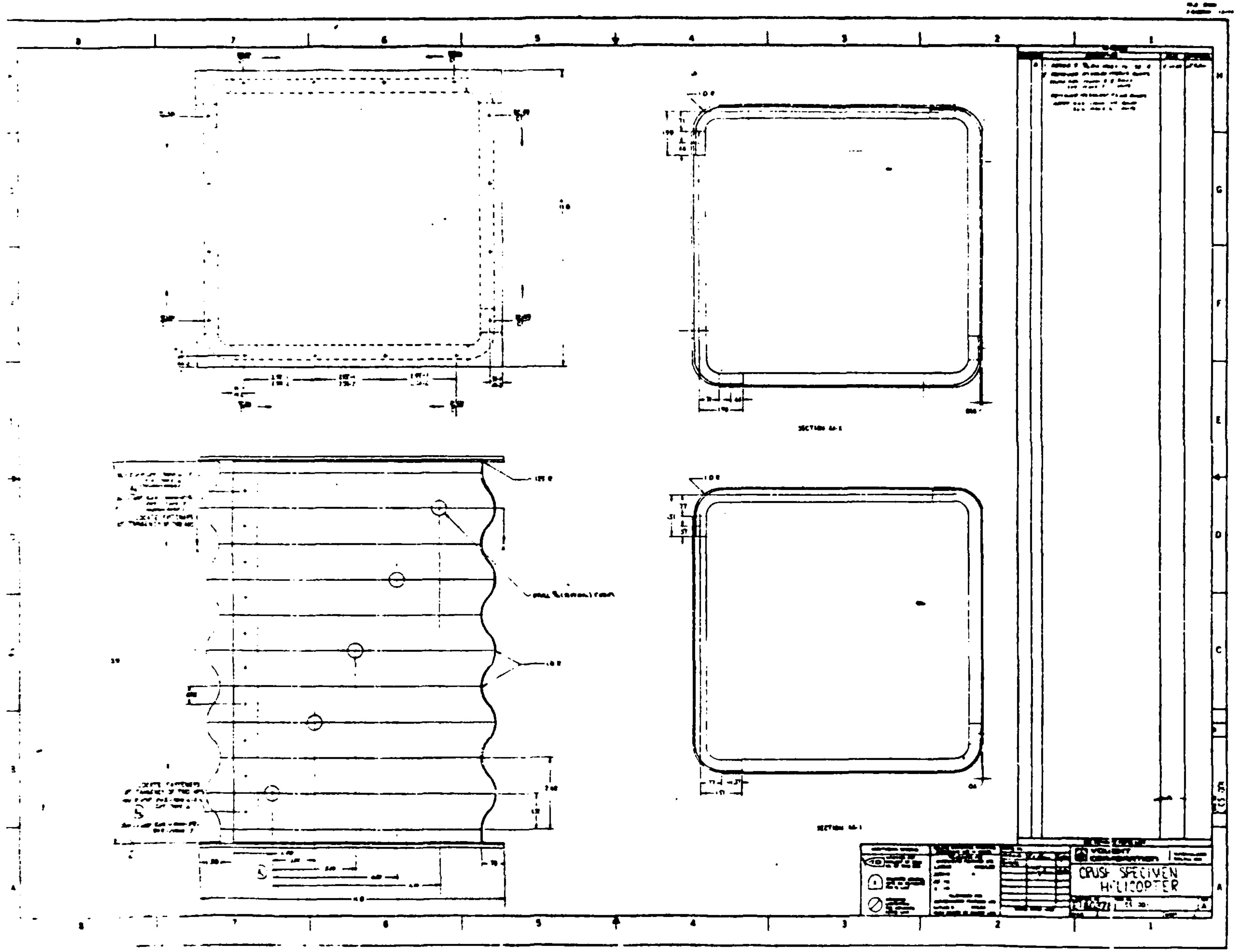


Figure 12. Crush Test Specimen Drawing

# 4.0 TEST AND EVALUATION

## 4.1 Slow-Rate Test Results

### 4.1.1 Introduction

The slow-rate tests consisted of five segments (three 0.040 and two 0.063 inch thick). These thicknesses are the closest standard gages that match the design goals, while providing a good range of test data. This is desirable since other parameters can be varied (i.e., longeron and bulkhead geometry) to meet design requirements.

One specimen of each gage was used to investigate the performance of the fasteners located at the peaks and valleys of each sine wave. Energy efficiency was reduced on these specimens with considerable tearing at the structural joints; therefore, the configuration was dropped. Some blind fasteners pulled through the sheet on all test specimens because the bulb end of the blind fastener provided inadequate bearing surface in tension. This failure mechanism was particularly evident on the 0.040 inch gage specimens. Since blind fasteners were not a design requirement, and were selected for convenience, it was decided to change to Hilok fasteners with their superior tension capability. The fifth specimen (0.040 inch gage) was fabricated with HiLoks and tested. A marked improvement in energy efficiency was observed with no joint failures. Seven of the eight segments shipped to NASA for high-rate testing were reworked to incorporate this change. The eighth specimen was already at NASA. Since it was an 0.063 inch gage specimen, which was determined to have reduced fastener failure, it was not altered.

### 4.1.2 Specimens with Relocated Fasteners

Two specimens were used to evaluate optional fastener location. One specimen of each gage had blind fasteners installed at the peaks and valleys of the sine waves to simplify the manufacturing procedures. Figure 13 is a plot of the load/deflection curves for the two specimens. Curve B is the data from the 0.063 inch thick skin specimen. Peak loads of almost 12,000 pounds demonstrated that this configuration was unacceptable. Figure 14 is a photograph of the 0.063 inch thick skin specimen fully compressed and shows shear tear-out failures at the corners where the fasteners are in the peaks. Curve A on Figure 13 is the data from the 0.040 inch thick skin specimen. The overall load-carrying capability of this configuration was 57 lb/in., which is much less than the preliminary test result of 77.5 lb/in. The poor performance of both specimens eliminated the option of installing the fasteners at the sine wave peaks and valleys. All remaining specimens had fasteners installed at the sine wave tangency points.

### 4.1.3 Specimens with 0.040 Inch Thick Skins

Two 0.040 inch thick skin specimens were tested to evaluate their load carrying and energy absorption capability. The first test specimen had blind fasteners installed. Figure 15 includes a plot of the load/deflection (Curve A) for this specimen. Results indicate a desirable energy absorption curve and an average load carrying capability of 75.4 lb/in. This compares favorably with the 77.5 lb/in load carrying capability of the preliminary

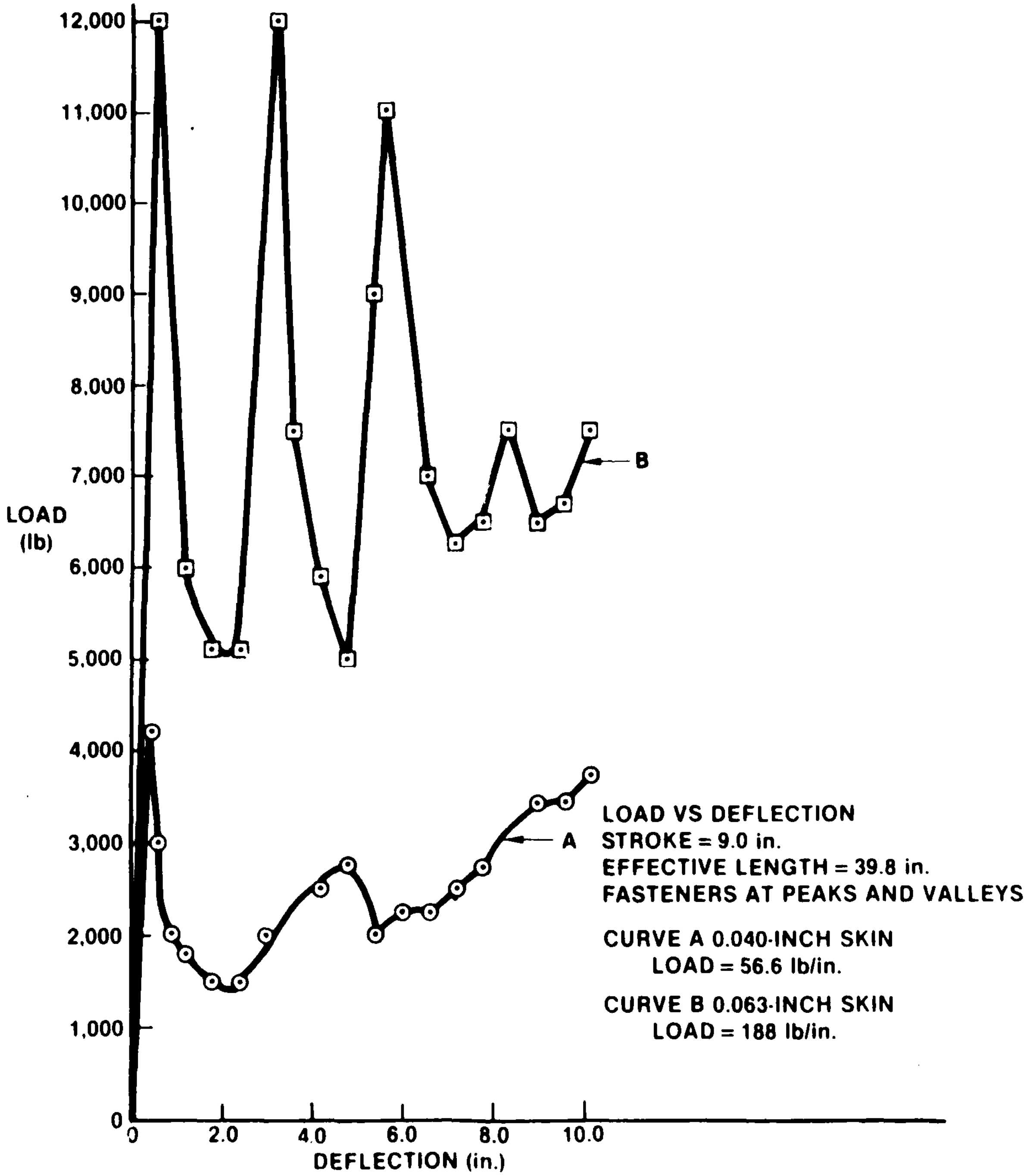


Figure 13. Load vs. Deflection for Specimens with Blind Fasteners at Peaks and Valleys

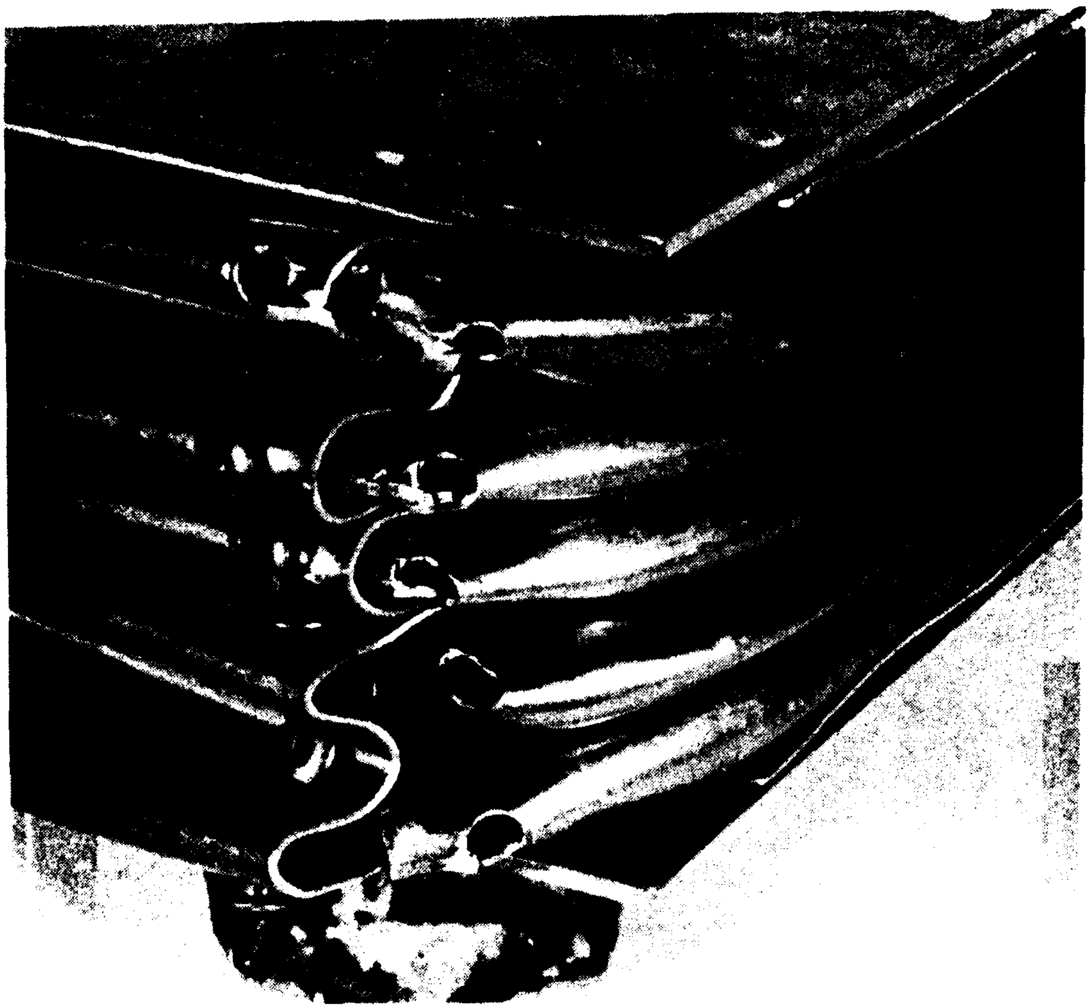

Figure 14. Test Specimen with Relocated Fasteners Showing Severe Fastener Failures at Edges

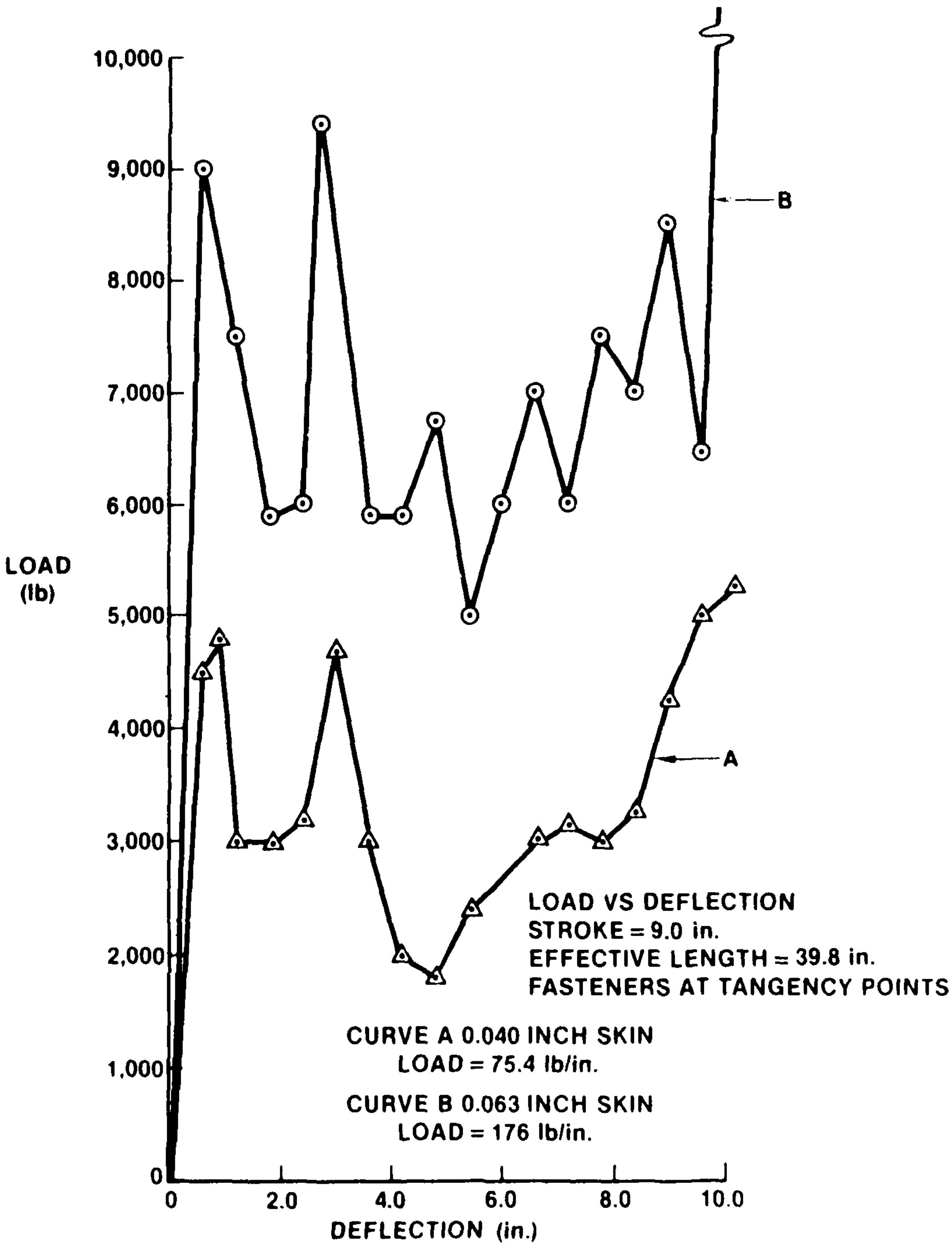


Figure 15. Load vs. Deflection for Specimens with Blind Fasteners at Tangency Points

test, except it had unpredicted fastener pullout at the corners. One difference between the preliminary test segment and this specimen was the addition of 16 vent holes drilled at the valleys of the sine waves. Another difference was that the earlier specimen was heat treated at a lower temperature for a longer period of time. Both cycles are accepted heat treatments for the T-6 condition. The vent holes account for the slightly lower load carrying capability of the more recent test specimen.

Due to the unpredicted pullout of the blind fasteners, an additional specimen was fabricated with HiLoks instead of the blind fasteners. Figure 16 is a plot of the load/deflection test results. Curve A is a replot of the 0.040 inch thick specimen with the blind fasteners. The specimen with HiLoks (Curve B) carried an average load of 88 lb/in, a 17 percent improvement in load and the curve indicates an improvement in energy absorption efficiency. None of the fasteners pulled out, and there was no shear tear-out at the edges. The HiLok fasteners obviously provided a superior joining technique; therefore, the fasteners were changed from blinds to HiLoks on the four remaining 0.040 inch thick specimens delivered to NASA.

### 4.1.4 Specimens with 0.063 Inch Thick Skins

Curve B of Figure 15 presents the load/deflection test results from the 0.063 inch thick specimen. It had a desirable energy absorption curve and load-carrying capability of 176 lb/in.

This was less than the 208 lb/in value on the preliminary test segment. Differences in specimen configuration included 16 vent holes in the sine wave valleys which would amount to approximately 3% strength reduction. Since the strength reduction was 15%, this only accounts for a small percentage of the difference. Some additional joint failures were observed in the later test so the decision was made to incorporate the HiLok fastener change on the three remaining 0.063 inch thick specimens. (One had already been delivered to NASA).

The 0.063 inch gage specimen already sent to NASA was tested as it was, to provide high rate comparative test results between HiLok and blind fastening results.

## 4.2 High Rate Test Results

### 4.2.1 Instrumentation and Equipment

The high-rate tests were conducted at the Army Structures Lab at NASA Langley with their IMPAC 1212 Shock Test Machine. Figure 17 is a photograph of the setup with specimen in place. The specimens were placed on the test machine base in a recessed area to restrain any unexpected lateral motion. The instrumented drop table, just above the specimen in the photograph, was raised to a height of 29.0 inches above the specimen during the actual tests. The drop table weighed 226 pounds and had three accelerometers (for redundancy) and a velocity marker mounted to it. The accelerometers, Endevco Model 7231C piezoresistive type with a maximum range of 750 g's, were bonded to rubber pads to attenuate the metal ringing effects. The three accelerometers were then fastened to the table. The velocity of the table at impact was

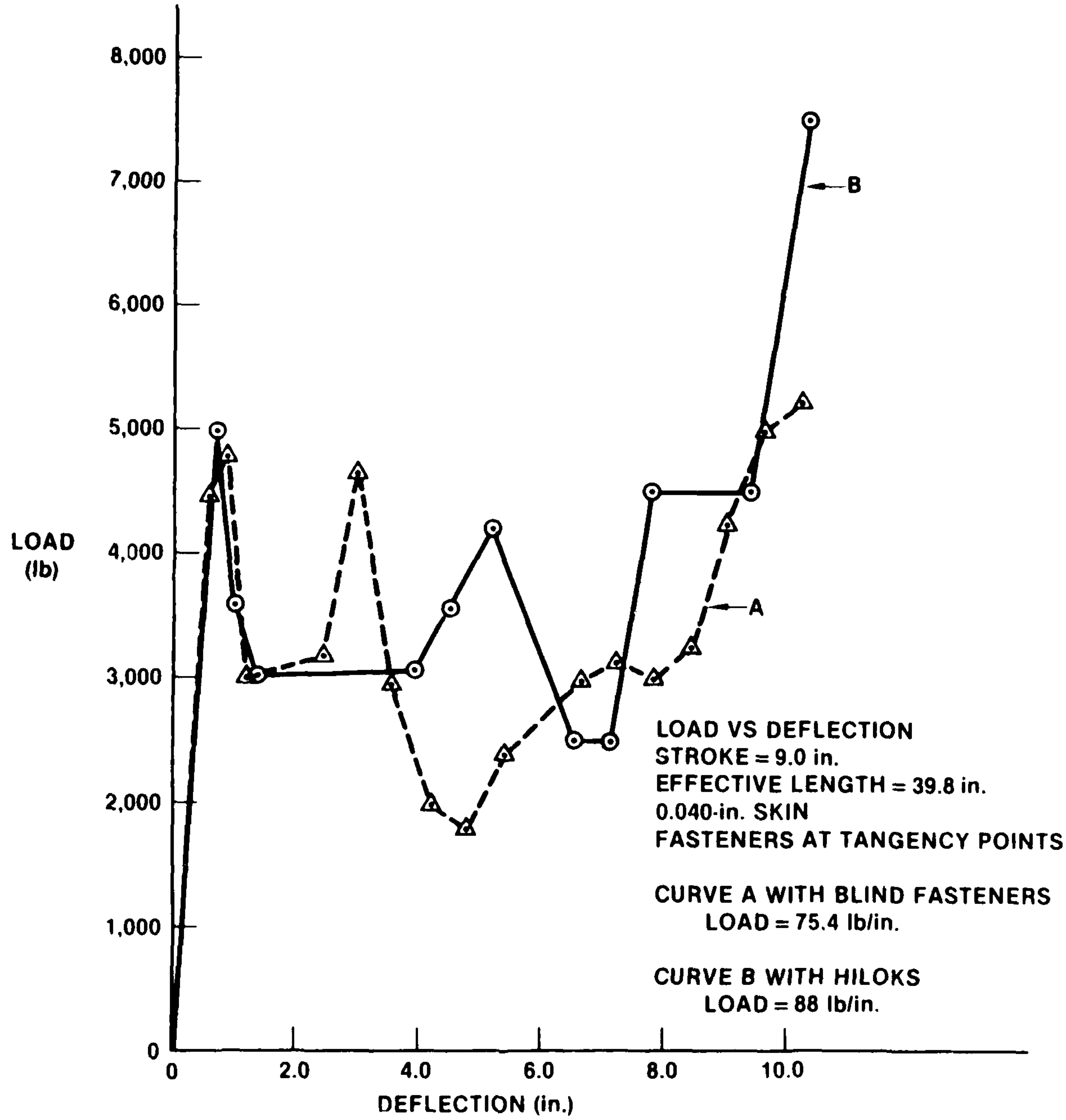


Figure 16. Load vs. Deflection for Specimens with Two Type Fasteners

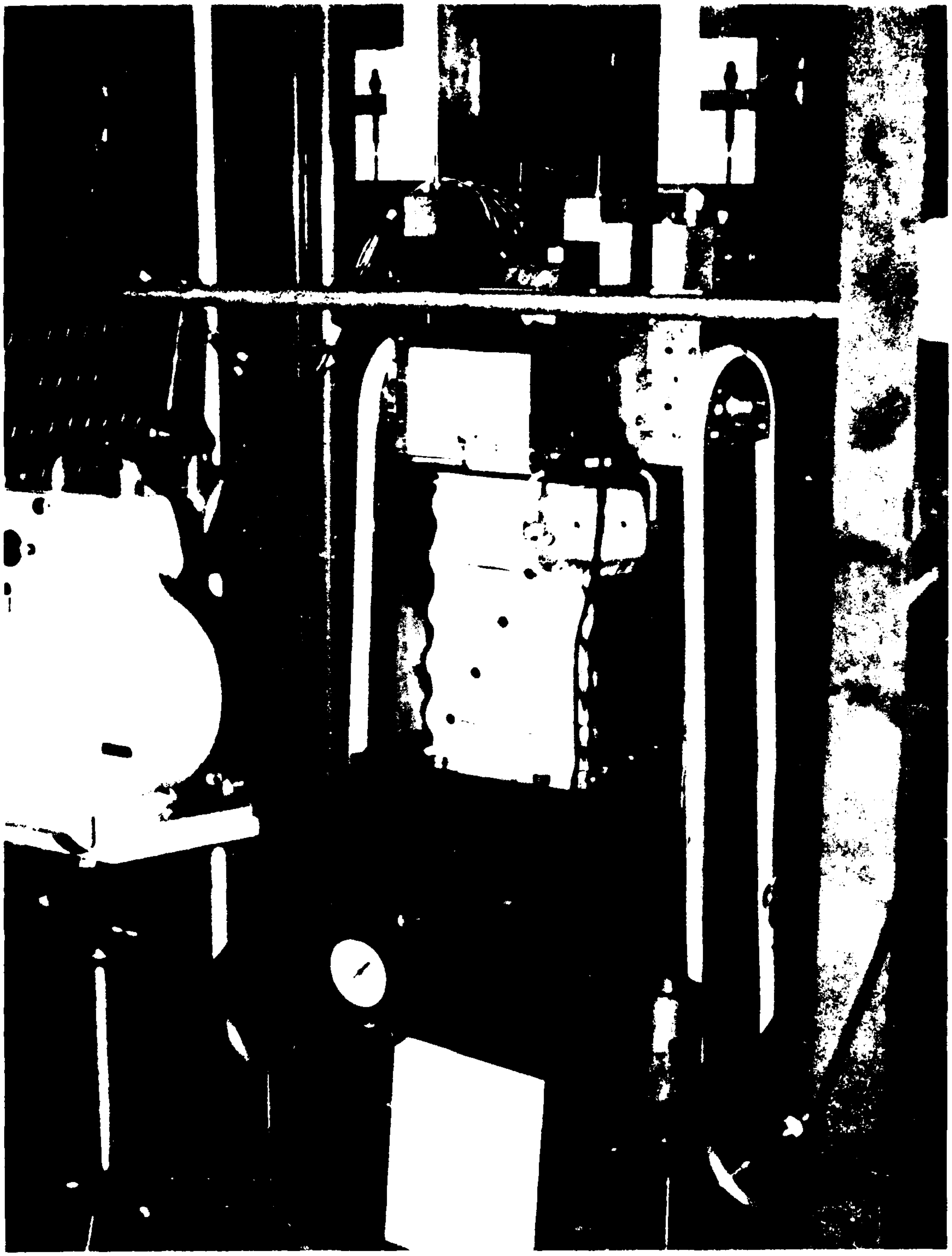

Figure [illegible]. Army Structures Lab High-Rate Test Machine
with Specimen

verified by the velocity marker which passed between two photoresistive transducers set exactly 1.0 inch apart. The photoresistive transducers recorded the time required for the marker to pass between them.

The high speed movie camera, at the left in the photograph, was used to verify symmetrical crush initiation and cross-check the velocity of the drop table at impact.

Two bungee cords were attached to either side of the table to increase the amount of energy the table could deliver. Figures 18 and 19 are calibration curves for the test machine with the bungees. The curves were developed by the Army Structures Laboratory for other test programs.

Figure 18 is a plot of impact velocity versus initial drop table height above the base. The curve was developed by raising the drop table to various heights above the base, releasing it, and measuring the velocity at 4.0 inches above the base. For the Vought high-rate tests, the table was raised 29.0 inches above the specimens and released, corresponding to an initial impact velocity of approximately 32 ft/sec.

Figure 19 is a plot of residual bungee force versus height of the drop table above the base. This represents the additional force acting on the specimens during and after impact. The total force acting on the specimen during impact is this residual force plus 226 times the "g" value recorded in the accelerometer data. NEFF model amplifiers were used to amplify and convert the voltage output from the accelerometers to "g" values. The amplifiers were calibrated at 250 "g" equal to 1.0 volt.

An IRIG Model A Time Code Generator was used in conjunction with the accelerometer data to generate the "g" versus time data which was then recorded on a Bell and Howell 14 channel analog tape recorder. A Techtronix oscilloscope was also incorporated into the system for immediate visual inspection of the acceleration versus time data. Figure 20 is a photograph of the data acquisition system.

The analog tape from the recorder was converted to digital data and output in tabular form as acceleration, in units of "g's" at time intervals of approximately $6 \times 10^{-6}$ seconds. Test results of the 0.040 inch and the 0.063 inch thick specimens are discussed in the next two sections.

### 4.2.2 Thin Gage Specimen Test Results

The 0.040 inch specimens collapsed to an average height of 3.0 inches. This was based on measuring and averaging the heights of the four corners of all four specimens. No corner was more than 0.125 inch above any of the other corners of each specimen. The crush initiated at the top of the specimen. This is desirable because the drop table simulated the ground striking the bottom of the helicopter.

Figure 21 is a plot of acceleration in "g's" versus time in milliseconds for the first specimen. It is typical of the other three 0.040 inch gage test specimens. Initially the curve is relatively flat with no severe initial spike but a large spike at the end. The peak load at the end was due to the large mass of the drop table which developed more total energy than anticipated. The drop table weight should have been 119 lbs.

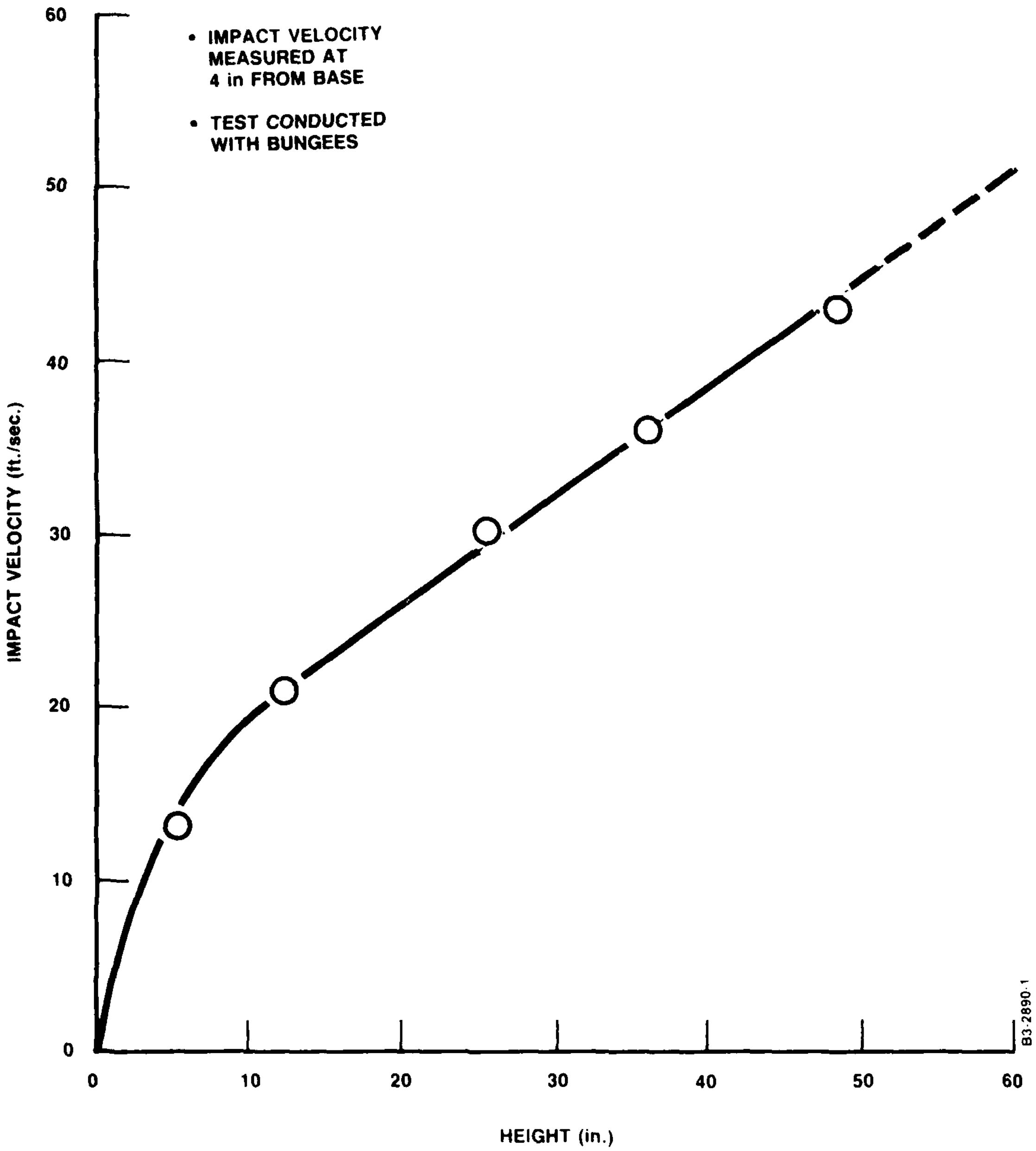


Figure 18. Impact Velocity vs. Height

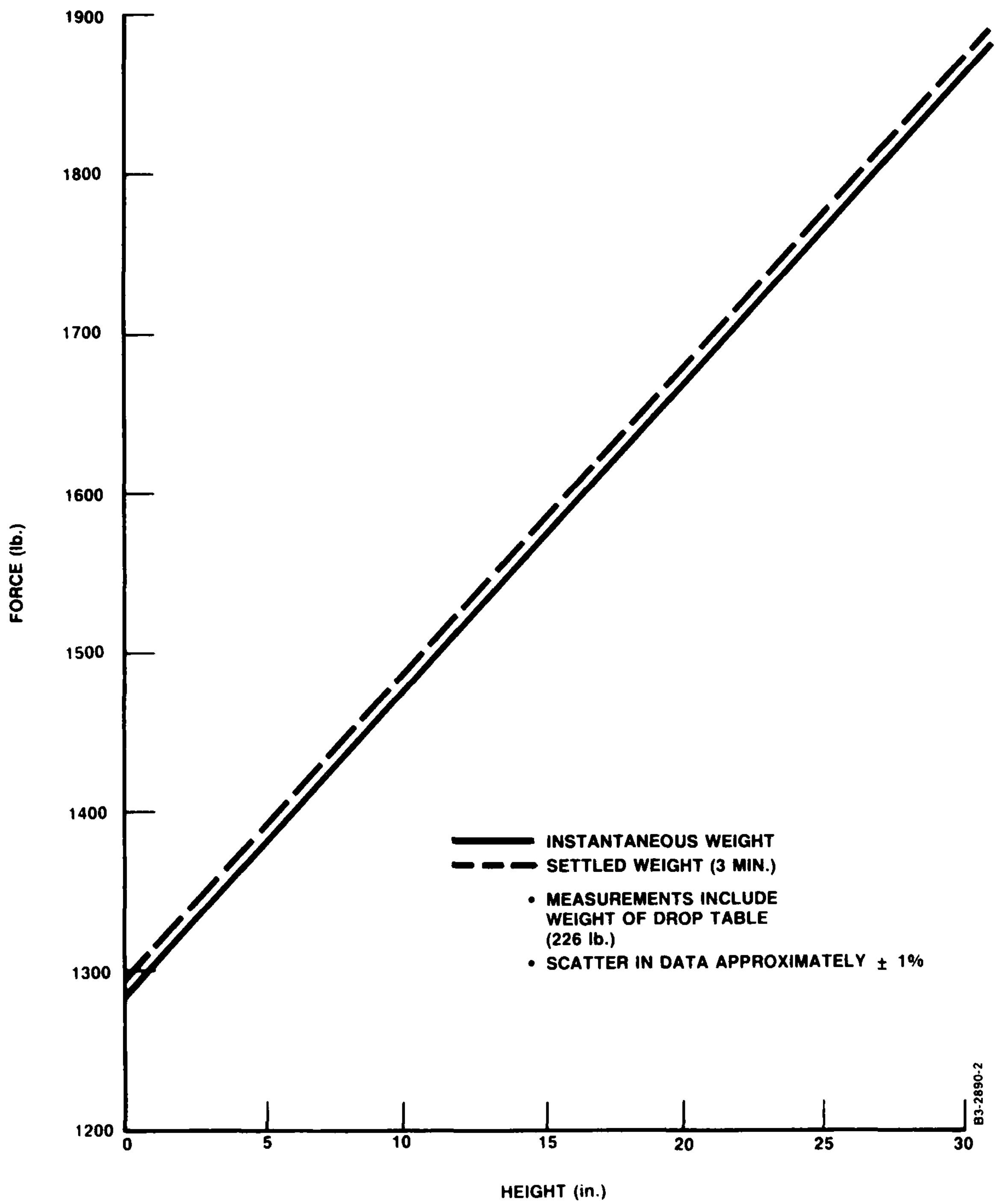


Figure 19. Bungee Force vs. Height

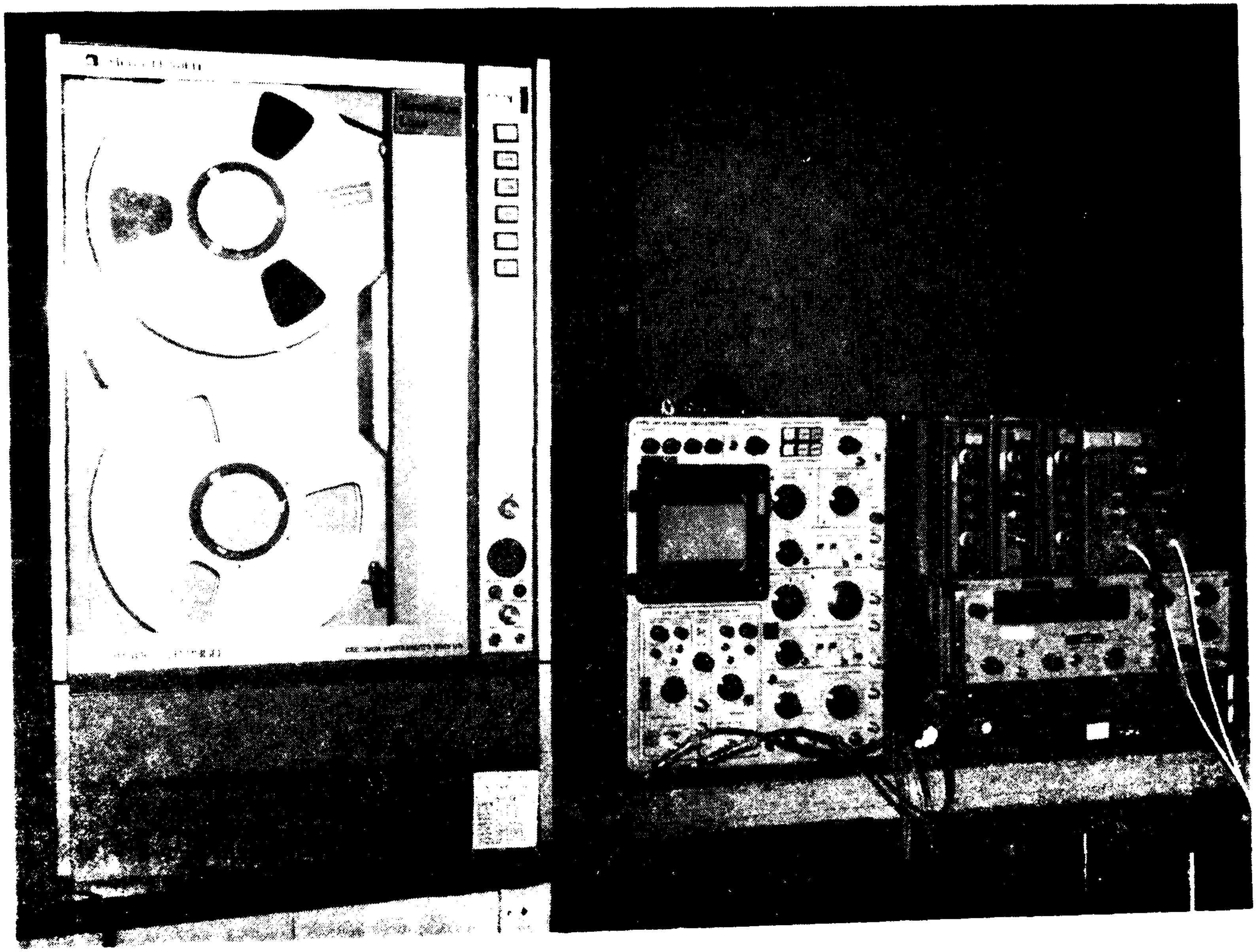

Figure 20. Data Acquisition System

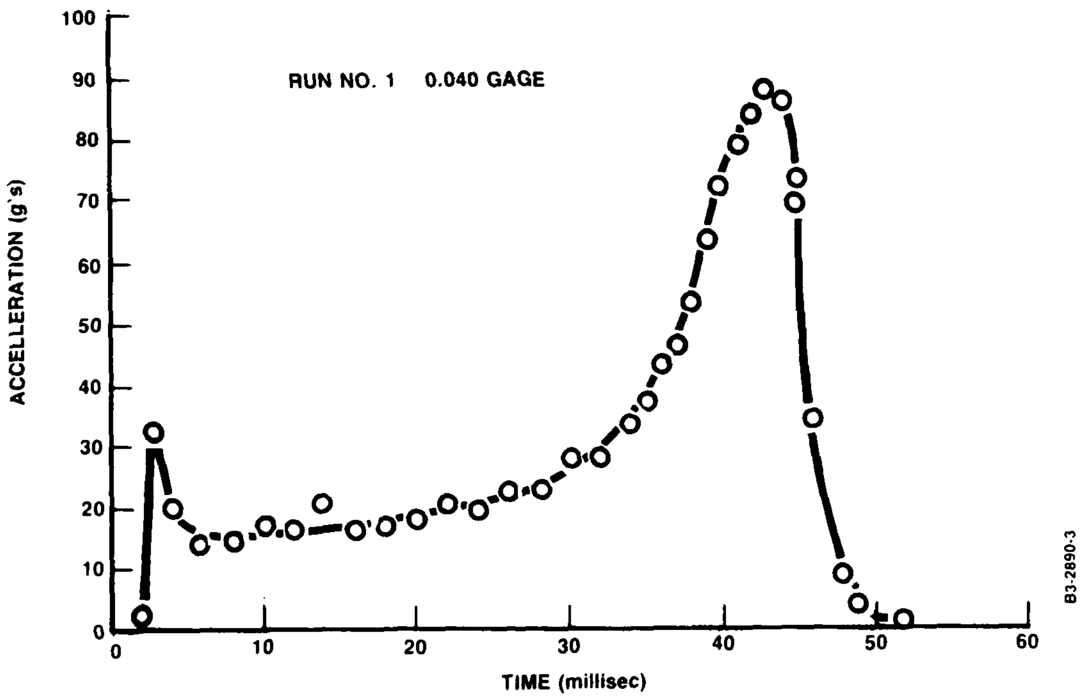


Figure 21. Acceleration vs. Time for Thin Gage Specimens

The four specimens sustained an average load of 18 g's over the first 35 milliseconds, which corresponds to the following loading:

$$18 \times 226 + (1480-226) = 5322 \text{ pounds.}$$

This represents a linear loading of:

$$\frac{5322 \text{ lbs}}{39.3 \text{ in}} = 135 \ \frac{\text{lb}}{\text{in}}$$

This is 35 percent better than the design goal of 100 lb/in for the 0.040 inch gage specimens.

The time interval of 35 milliseconds was selected because of the acceleration peak after 35 milliseconds. The peak was created by the 226 pound drop table weight (as opposed to the required weight of 119 pounds).

4.2.3 Thick Gage Specimen Test Results

The 0.063 inch specimens collapsed to an average height of 6.2 inches. This was based on measuring and averaging the heights of the four corners of the four specimens. No corner was more than 0.125 inch above any other corner of each specimen.

Figure 22 is a plot of acceleration in "g's" versus time in milliseconds for the first 0.063 gage specimen. It is typical of the other three. Initially, the shape corresponds to peak g's as a corrugation peak collapses. After 30 milliseconds the energy is attenuated at a constant rate.

The four specimens sustained an average load of 35 g's which corresponds to the following loading:

$$35 \times 226 + (1480-226) = 9164 \text{ pounds.}$$

This represents a linear loading of:

$$\frac{9164 \text{ lbs}}{39.3 \text{ in}} = 233 \ \frac{\text{lb}}{\text{in}}$$

This is 16 percent better than the design goal of 200 lb/in. These tests substantiate the energy absorbing capability of the rotated sine wave concept. The specimens collapsed only 6.2 inches because the drop table weight was 226 pounds instead of the required 308 pounds.

Figure 23 is a photograph of the thick gage specimen after test. The stroke is approximately 56 percent of the expected value.

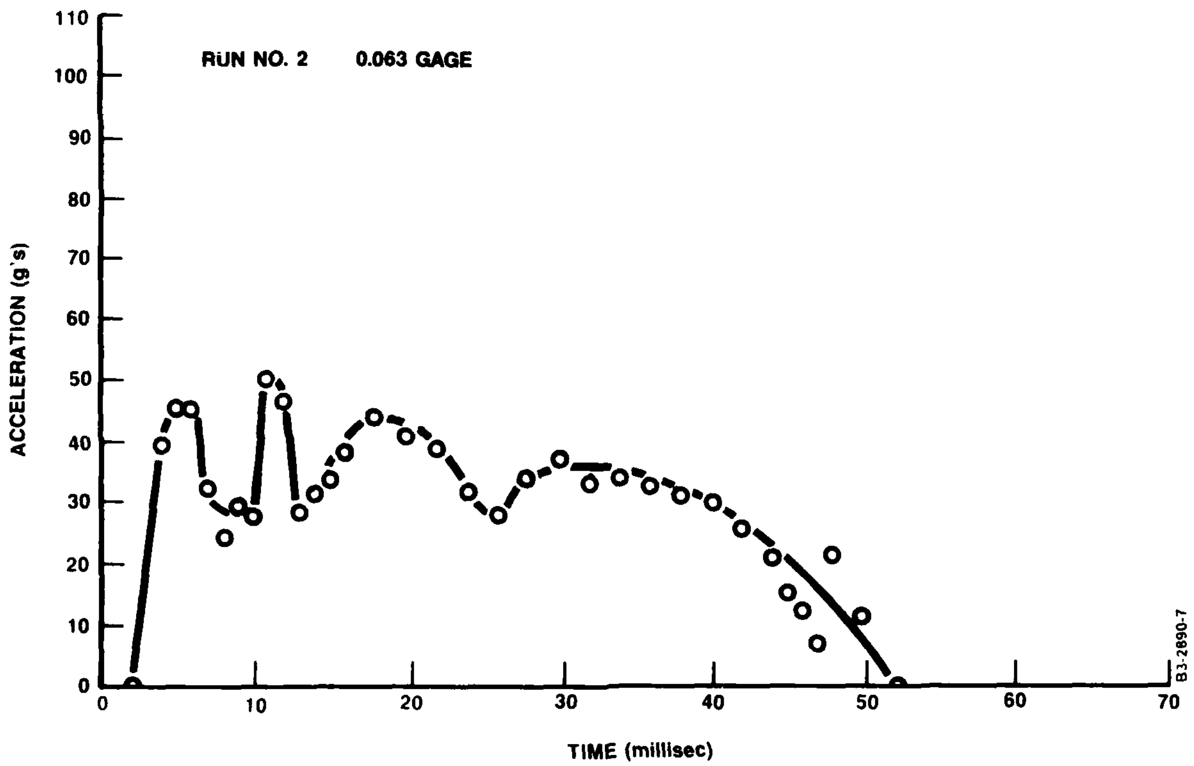


Figure 22. Acceleration vs. Time for Thick Gage Specimen

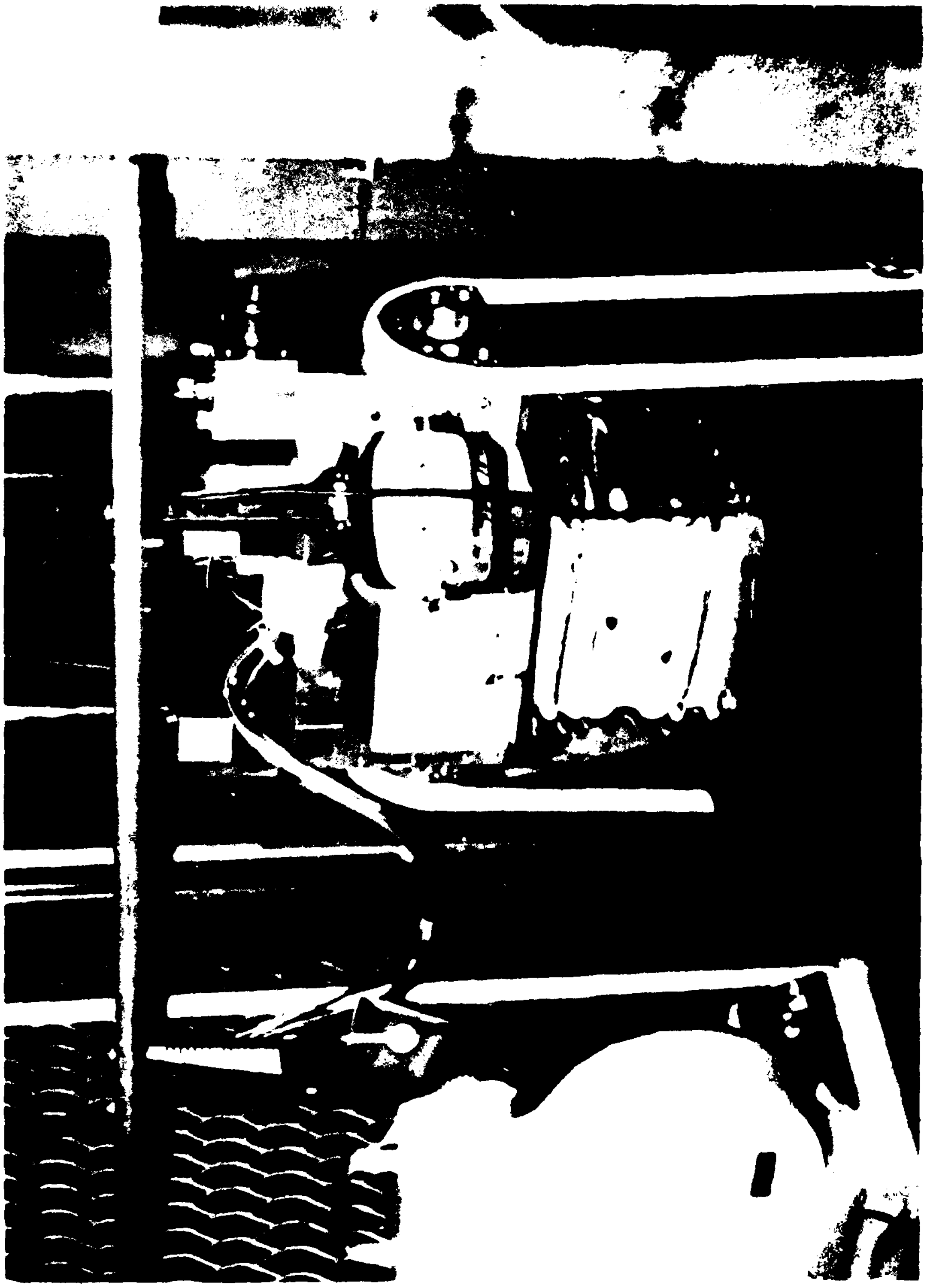

Figure 23. Crushed Thick Gage Specimen

## 5.0 PAY-OFF ANALYSIS

The purpose of this section is to present the pay-off analysis for the energy absorbing structure developed in this program. The results of previous government sponsored programs are presented first. This provides the weight and performance criteria used to evaluate the energy absorbing efficiency of the rotated sine wave concept. Next, the low-rate and high-rate energy absorbing test results from the various programs are compared. Finally, a cost analysis is performed to compare the sine wave structure to conventional structure with advanced manufacturing techniques.

### 5.1 Previous Industry Program Results

This section presents the results of previous programs that structurally tested energy absorbing configurations for flight vehicles and compares them to the results from this program. Tables 2, 3 and 4 present the energy absorbing efficiency of several material and design configurations developed using slow rate test procedures. Specific details for each chart are discussed below.

The running loads shown in column 3 of the tables were calculated by dividing the average post ultimate load of each test specimen by the perimeter of the specimen. Specific running loads are these running loads divided by the product of material thickness multiplied by the density. The work shown in column 5 of the tables was determined by multiplying the running load by the vertical distance or stroke the loading head travelled. This represents the total energy absorbed by each configuration. Specific work was calculated by dividing the work by the same factor used for the specific running load. This allows for a comparison between different materials and different structural configurations.

Table 2 is from Reference 1, reported in October 1982. The test elements utilized 9.0 inch diameter vertical tubes fabricated in three configurations with four materials each. The three configurations were internally stiffened (IS), externally stiffened (ES) and honeycomb sandwich construction (HC). The materials evaluated were aluminum (Al), graphite/epoxy (Gr/Ep), Kevlar/epoxy (K/Ep), and fiberglass/epoxy (Gl/Ep).

Conclusions based on this table are: (1) the vertical tube creates a large initial peak load, making it an ineffective configuration, (2) aluminum is excellent for energy absorbtion in all configurations and (3) the composites are best utilized in honeycomb sandwich construction.

Table 3 presents a summary of the results developed in Reference 2. Several general aviation aircraft structural configurations were evaluated but only two were of interest and are presented. The corrugated structure is presented because it led to the Vought concept (which is simpler and less costly to fabricate than what is shown in Reference 2). The horizontal tube configuration is shown because it included another comparison between aluminum and Kevlar. The results indicate the advantages of the horizontal tubes; however, they are difficult to incorporate into actual floor substructure, i.e., attach floor structure or seat tracks and develop effective structural intersections.

TABLE 2. ENERGY ABSORPTION SLOW-RATE TEST SUMMARY (REFERENCE 1)

| MATERIAL<br>THICKNESS<br>DENSITY | Stiffener Configuration | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | INTERNAL | | | | | EXTERNAL | | | | |
| | LOAD LBS. | RUNNING LOAD $\frac{lbs}{in}$ | SPECIFIC RUNNING LOAD $\times 10^{-3}$ | WORK $\frac{lb\ In.}{in}$ | SPECIFIC WORK $\times 10^{-3}$ | LOAD LBS. | RUNNING LOAD $\frac{LBS}{IN}$ | SPECIFIC RUNNING LOAD $\times 10^{-3}$ | WORK $\frac{LBS\ IN}{IN}$ | SPECIFIC WORK $\times 10^{-3}$ |
| Aluminum<br>$\bar{t}$ = .037 in.<br>$\rho$ = .100 $\frac{lbs}{in^3}$ | 9000 | 318 | 85.9 | 1591 | 430 | 5000 | 177 | 47.8 | 884 | 239 |
| Gr/Ep<br>$\bar{t}$ = .059 in.<br>$\rho$ = .056 $\frac{lbs}{in^3}$ | 850 | 30 | 9.1 | 150 | 45.4 | 1000 | 35 | 10.6 | 177 | 53.6 |
| K/Ep<br>$\bar{t}$ = .077 in<br>$\rho$ = .066 $\frac{lbs}{in^3}$ | 850 | 30 | 6.1 | 150 | 29.4 | 1000 | 35 | 6.9 | 177 | 34.7 |
| GI/Ep<br>$\bar{t}$ = .074 in.<br>$\rho$ = .066 $\frac{lbs}{in^3}$ | 3150 | 111 | 22.6 | 557 | 113.7 | 1200 | 42 | 8.6 | 212 | 43.3 |

Stroke = 5.0 In. Perimeter = 28.3 In.

TABLE 2. ENERGY ABSORPTION SLOW-RATE TEST SUMMARY (REFERENCE 1), cont.

| MATERIAL THICKNESS DENSITY | CONFIGURATION: HONEYCOMB | | | | |
|---|---|---|---|---|---|
| | LOAD LBS. | RUNNING LOAD $\frac{LBS}{IN}$ | SPECIFIC RUNNING LOAD x $10^{-3}$ | WORK $\frac{LBS}{IN}$ | SPECIFIC WORK X $10^{-3}$ |
| Aluminum $\bar{t}$ = .034 in $\rho$ = .100 $\frac{lb}{in^3}$ | 9400 | 332 | 100. | 1662 | 504 |
| Gr/ Ep E = .048 in. $\rho$ = .056 $\frac{lb}{in^3}$ | 5600 | 198 | 73.7 | 990 | 368 |
| K/Ep $\bar{t}$ = .063 in. $\rho$ = .056 $\frac{lb}{in^3}$ | 6400 | 226 | 54.4 | 1132 | 272 |
| Gl/Ep $\bar{t}$ = .063 in. $\rho$ = .066 $\frac{lb}{in^3}$ | 8200 | 290 | 69.7 | 1450 | 349 |

Stroke = 5.0 In. Perimeter = 28.3 In.

TABLE 3. ENERGY ABSORPTION SLOW-RATE TEST SUMMARY (REFERENCE 2)

| | Configuration | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CORRUGATION | | | | | | | TUBE | | | | | | |
| | LOAD LBS. | RUN IN | RUNNING LOAD $\frac{lbs}{in}$ | SPECIFIC RUNNING LOAD $\times 10^{-3}$ | STROKE IN | WORK $\frac{IN\text{-}LBS}{IN}$ | WORK $\times 10^{-3}$ | LOAD LBS. | RUN IN. | RUNNING LOAD $\frac{LBS}{IN}$ | SPECIFIC RUNNING LOAD $\times 10^{-3}$ | STROKE IN. | WORK $\frac{IN\text{-}LBS}{IN}$ | SPECIFIC WORK $\times 10^{-3}$ |
| Aluminum $\bar{t}$ = .064 in. $\rho$ = .100 $\frac{lb}{in^3}$ | 372 | 5.5 | 67.6 | 10.5 | 4 | 270 | 42 | | | | | | | |
| Aluminum $\bar{t}$ = .032 in $\rho$ = .100 $\frac{lb}{in^3}$ | 82 | 5.5 | 14.9 | 4.6 | 4 | 60 | 18.4 | | | | | | | |
| Aluminum $\bar{t}$ = .100 $\rho$ = .100 | | | | | | | | 1200 | 6 | 200 | 15.4 | 6 | 1200 | 237 |
| K/$E_D$ $\bar{t}$ = .11 $\rho$ = .66 | | | | | | | | 1100 | 6 | 183 | 19.3 | 6 | 1098 | 116 |
| K/$E_D$ $\bar{t}$ = .22 $\rho$ = .066 | | | | | | | | 600 | 6 | 100 | 6.1 | 6 | 600 | 3[illegible] |

TABLE 4. ENERGY ABSORPTION SLOW-RATE TEST SUMMARY (VOUGHT)

| MATERIAL<br>THICKNESS<br>DENSITY | Configuration | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SINEWAVE | | | | | | | INTERNAL STIFFENED | | | | | | |
| | LOAD LBS. | PERIMETER RUNNING IN | RUNNING LOAD $\frac{lbs}{in}$ | SPECIFIC RUNNING LOAD x $10^{-3}$ | STROKE IN | WORK $\frac{lb}{in}$ In. | SPECIFIC WORK x $10^{-3}$ | LOAD LBS. | PERIMETER RUNNING IN. | RUNNING LOAD $\frac{LBS}{IN}$ | SPECIFIC RUNNING LOAD x $10^{-3}$ | STROKE IN. | WORK LBS IN $\frac{}{IN}$ | SPECIFIC WORK x $10^{-3}$ |
| Aluminum<br>$\bar{t}$ = .063 in<br>$\rho$ = .100 $\frac{lbs}{in^3}$ | 7000 | 39 | 17[illegible] | 28.9 | 8 | 1432 | 227 | | | | | | | |
| Aluminum<br>$\bar{t}$ = .040 in<br>$\rho$ = .100 $\frac{lbs}{in^3}$ | 3000 | 39 | 77 | 19.4 | 8 | 616 | 154 | | | | | | | |
| K/Ep<br>$\bar{t}$ = .090 in<br>$\rho$ = .066 $\frac{lbs}{in^3}$<br>(ACAP) | | | | | | | | 7000 | 96 | 73 | 27.6 | 4 | 292 | 111 |

Table 4 presents the Vought slow-rate test results. Two different material gages in the sine wave configuration were evaluated to develop a design curve of running load (lb/in) versus substructure thickness (in.). The Kevlar data is from the earlier effort at Vought on the ACAP program.

## 5.2 Performance Comparison

The performance advantages of the rotated sine wave design are indicated by comparing the slow-rate test results with other industry results.

The rotated sine wave concept has comparable or better energy absorption characteristics than any other configuration and it is the simplest to incorporate into fuselage structure. It can be designed to carry required flight loads and crush at the predetermined rate to improve the survivability of the crew and passengers in the vehicle. The energy absorbing structure would be used throughout the entire substructure area, between the floor and outer skin, allowing cutouts for systems requirements, yet still able to sustain a crash. The crushed rotated sine wave also demonstrated excellent post crush structural integrity. There was no fragmentation (i.e., no fasteners flying apart), the specimens crushed from the top down simulating the desired bottom-up on an actual flight vehicle, and it demonstrated the capability of maintaining the structural integrity of the floor. For these reasons, the rotated sine wave concept is the most practical and cost effective method of providing crash survivable structure for helicopters.

The following paragraph compares the high-rate test results of three material/design concepts. The first is the vertically stiffened concept made from Kevlar/epoxy. The average load it sustained of the initial peak was 77 lb/in, less than 50 percent of the 200 lb/in design goal. Since this configuration did not meet the design requirement, it was eliminated from further consideration. The second configuration was the composite concept discussed in Reference 3. It is a sandwich construction with Kevlar/epoxy facesheet and nomex honeycomb core. The design goal was 333 lb/in because the energy absorbing structure was used in selected areas only. The full scale drop test conducted with this configuration indicated an energy absorption of 296 lb/in, which gives 203,000 in-lb/in as the specific work. The third concept is the one developed in this program. Two different thicknesses were evaluated to develop a design methodology. The 0.040 inch gage specimen absorbed 135 lb/in which converts to 96,000 in-lb/in for specific work. The 0.063 inch gage specimens sustained 235 lb/in loading which converts to 197,000 in-lb/in.

A significant difference between the composite and metal configuration is that there was considerable development with the composite to tailor its performance. The metal design was basically a preliminary design for the dynamic tests. The initial spike which shows up on the test results could be eliminated by changing the sinewave pitch at the base and possibly adding cutout holes. The Phase II effort would verify these approaches.

## 5.3 Cost Analysis

The following analysis was performed to compare the cost of a "C-section" type longeron to the rotated sine wave configuration on a cost per foot of structure basis. The following assumptions were made in doing the calculations:

1. 1983 dollars, rounded to nearest dollar
2. Material Thickness:
   0.063 in. Sine Wave
   0.080 in. C-section
3. 500 parts made in lots of 10
4. Labor costs include manufacturing, quality, direct methods and tool maintenance.
5. Fastener costs are included for C-section material.
6. Amortized tooling costs include design, manufacture and material for all tooling fabrication:

COST SUMMARY

| | Sine Wave | C-Section |
|---|---|---|
| Materials | $ 9.00 | $17.00 |
| Labor | 20.00 | 21.00 |
| Amortized Tooling | 3.70 | .80 |
| TOTAL | $33.00 | $39.00 |

Both have low labor hours because of automated fastener preparation and installation (DRIVEMATIC). The tooling cost for the rotated sine wave is higher because each part needs a tool versus the segmented radius blocks used for conventional structure. As the number of parts fabricated increases, the tooling is amortized over a larger number of parts; consequently, the cost per part decreases. The overall advantage of 500 sine wave parts is:

$$\frac{39-33}{39} \times 100 = 15\%.$$

## 6.0 CONCLUSIONS

This section presents conclusions based on the results of this program. The areas discussed include manufacturing, cost, weight and performance.

Fabrication of the thirteen test specimens for this program provided invaluable manufacturing experience. The specimens were fabricated in a standard sheet metal shop, without special attention. The room temperature hydroforming process has a low energy input requirement and the assembly is adaptable to automatic fastening techniques. There was no measurable wear on the plastic tool after fabrication of the skin panels and no tolerance problem in fitting the skin panels together.

There are several cost and weight advantages associated with the sine wave concept. The cost savings relative to conventional metal design are attributable to the reduction in number of parts and fasteners which saves material dollars and assembly hours. Potential cost savings relative to the composite structure would be due to lower material cost and less expensive fabrication methods (i.e., hydroform versus autoclave). The weight savings versus conventional metal are also due to part count reduction.

The high-rate and slow-rate testing of the test elements verified the performance of the energy absorbing structure developed in this program. The slow-rate testing provided design data for developing the high-rate specimens. The initial spikes were due to the additional load needed to initiate buckling. There are several solutions which can be incorporated into the design to eliminate these spikes. There was no fragmentation during the high rate testing. The structure remained intact and could provide the required amount of support to the floor and seat support structure during and after a crash.

The selected skin gage to meet the 200 lb/in running load requirement is 0.063 inches. The substructure will carry normal flight loads and provide the energy absorbing capability when necessary.

The aluminum structure would be less susceptible than honeycomb to the effects of moisture and cutouts for hydraulic and electrical systems, than would the honeycomb structure. Therefore, the substructure could be continuous under the entire fuselage section.

## 7.0 RECOMMENDATIONS

Based on the results of this investigation, it is recommended that:

(1) Detail design of a complete helicopter subfloor structure should be performed. This would include determining exact requirements for the helicopter system under evaluation and conducting additional testing on scaled up multi-bay specimens.

(2) Tooling should be scaled up. The basic tooling and manufacturing technology has been proven but variable depth beams need further investigation.

(3) A direct comparison of metal and composite full scale crashworthy structure, designed and tested using the same criteria, should be performed to quantify the differences in the crash impact behavior of the two types of materials.

## 8.0 REFERENCES

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2. "Crashworthy Airframe Design Concepts, Fabrication and Testing"; J. D. Cronkhite, V. L. Berry; NASA CR 3603.

3. "Investigation of the Crash-Impact Characteristics of Advanced Airframes Structures"; J. D. Cronkhite, T. J. Haas, V. L. Berry, R. Winter; USARTL-TR-79-11.

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